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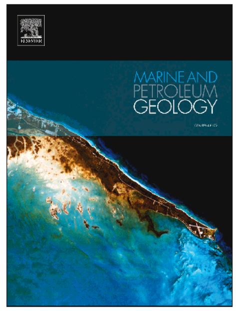

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National Gas Hydrate Program Expedition 02: Identification of gas hydrate prospects in the Krishna-Godavari Basin, Offshore India

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Abstract

After completing the first expedition of India's National Gas Hydrate Program (NGHP-01) in 2006, it was concluded that for the next expedition (National Gas Hydrate Program 02; NGHP-02), a new drill site review effort should focus on identifying potential deep-water offshore gas hydrate accumulations in sand dominated depositional environments. Therefore, geological and geophysical data analysis and 3D seismic data interpretation along with associated seismic modeling were carried out in three areas of the Krishna-Godavari Basin: Areas B, C, and E. Conventional petroleum exploration approaches of seismic amplitude evaluation were adapted to prospect for potentially sand-rich depositional systems within the gas hydrate stability zone. Subsequently, these prospective areas were further assessed through the geological and geophysical evaluation of depositional setting, gas sources, and gas migration pathways. In Area B, prospecting focused on a large anticlinal structure with a prominent bottom-simulating reflector and several key horizons that indicated evidence for potential sand-hosted hydrate occurrences. In Area C, the prospects were distributed throughout various settings within a very large deep-water channel-levee-fan system with complex indications of potential gas hydrate occurrence in sand-prone seismic facies. In Area E, prospects were associated with high amplitude events within inferred channel-levee sequences. Based on the pre-expedition/onboard drill-site evaluation, the 22 most promising sites in the Krishna-Godavari Basin were identified and prioritized to investigate and delineate a total of 17 identified gas hydrate prospects. This paper describes the geo-scientific studies carried out prior to NGHP-02 for site identification, evaluation and prioritization. An important outcome of this study is the identification of two potentially producible gas hydrate systems inferred to host significant quantities of gas hydrate in stratigraphic-structural traps.

Key Words: *Gas hydrate sand reservoir, Seismic, Gas hydrate proxy, Base of Gas Hydrate Zone (BGHZ), Gas Hydrate Petroleum System, NGHP-02, Bottom-Simulating-Reflector, Seismic Evidences, Seismic attributes, Reservoir identification, Gas hydrate characterization*

1. Introduction

Gas hydrates are considered to be a vast potential energy resource for the future *(Collett, 2002; Boswell and Collett, 2011).* In order to develop this important energy resource for India, the National Gas Hydrate Program (NGHP) was established in 1997. Under the National Gas Hydrate Program 01 (NGHP-01) Expedition, the first gas hydrate scientific drilling was conducted in the offshore of India in 2006 *(Kumar, et al., 2014; Collett et al., 2014),* which documented the occurrence of natural gas hydrate deposits in Indian deep water areas, particularly in the Krishna Godavari (KG) Basin (Figure 1). However, the gas hydrates observed in NGHP-01 were distributed primarily in fractured shale and clay dominated reservoirs for which no feasible production technology has yet been developed (*Boswell et al., 2014*). Therefore, a second drilling expedition, National Gas Hydrate Program 02 (NGHP-02), was specifically planned to discover gas hydrate occurrences in sand dominated reservoirs in the Eastern Offshore of India. As the greatest potential for sand deposition along the eastern margin of India lies near the toe of the continental slope, geo-scientific studies were carried out from 2008 to 2013 in water depths greater than 1500 m, which is deeper than the sites tested during NGHP-01 (<1500m) in KG Basin. During NGHP-02 in 2015, the sites identified in both the KG Basin and the Mahanadi Basin were investigated by 42 boreholes, including 25 LWD holes with the remaining holes dedicated to coring, wire line logging, and wireline formation testing (*Collett et al., this issue; Shukla et al., this issue*). The 25 drill sites established during NGHP-02 were selected to investigate 17 prospects (associated with 22 drill sites) in the KG Basin and 3 prospects (associated with 3 drill sites) in Mahanadi Basin identified in pre-drilling analysis.

The pre-drill prospecting effort followed the gas hydrate petroleum systems approach (*Collett et al., 2009; Max and Johnson, 2014; Boswell et al., 2016*) and included:

- Establishing the extent of the gas hydrate stability zone and position of bottom simulating reflector (BSR),
- Evaluating the seismic evidences for gas sourcing and migration into the gas hydrate stability zone (GHSZ),
- Evaluating the depositional environment for occurrence of coarser grain sediments within the GHSZ,
- Identifying seismic and geologic features that directly indicate the presence of gas hydrate within the GHSZ.

The above studies were carried out for three prospective areas covered by conventionally acquired and processed marine streamer 3D seismic data. These areas were designated for operational purposes as Areas B (Vizag), C (Godavari), and E (Krishna) in the KG Basin (Figure 1). In each area, a detailed review of the shallow sedimentary section was conducted to identify potential direct indications of gas hydrate. For each identified prospect, amplitude attributes were extracted and mapped to support geologic interpretations of the prospect setting and nature. The most promising sites were then recommended for NGHP-02 drilling. This paper summarizes the workflow adapted for the mapping/attribute analysis and petroleum systems evaluation conducted for the pre-expedition drill site evaluation for NGHP-02.

2. Background

Gas hydrate research in India received a boost when dedicated gas hydrate drilling, logging, and coring operations were successfully carried out under NGHP-01 at 21 sites (total 39 gas hydrate research wells) in four Indian Offshore basins (KG, Mahanadi, Andaman and Kerala-Konkan Basins) in 2006. NGHP-01 established that significant gas hydrate deposits are present in the Indian deep offshore areas - particularly in the East Coast and Andaman regions (*Shukla et al., 2012; Collett et al., 2014; Kumar et al., 2014*). However, gas hydrates encountered in NGHP-01 were predominantly distributed in clay dominated sediments. Given that no production concepts have yet been demonstrated to enable viable gas extraction from hydrates enclosed in clays (*Moridis and Sloan, 2007*: *Collett et al., 2009; Boswell et al., 2014*), gas hydrate resource evaluation in India shifted focus to the evaluation of evidence for gas hydrate in sand-rich reservoir systems for which field tests have demonstrated the technical feasibility of production (*Dallimore et al., 2012; Konno et al., 2017*).

From 2007 to 2013, an evaluation of approximately 7000 km^2 within KG Basin was conducted using the 2D and 3D seismic data acquired for conventional hydrocarbon exploration. The work included post stack processing and conditioning of the 3D seismic data, seismic event/horizon identification and correlation, subsurface relief map generation, seismic amplitude attribute analysis, and identification of seismo-geological features at and below the sea floor.

In general, the acquisition and processing of these seismic data were carried out for deeper conventional oil and gas exploration targets. Therefore it is considered that shallow seismic data processing was not appropriately constrained in the processing sequence. For this study, seismic data analysis was focused primarily on the shallow sedimentary section, but no special processing was done to enhance the gas hydrate reservoir properties.

The above studies culminated in geological and geophysical modeling for identification of sand bearing strata within the gas hydrate stability zone and selection of prospective sites for NGHP-02. In addition, geophysical studies conducted as part of the NGHP drill site review effort by Oil and Natural Gas Corporation (ONGC), Reliance Industries, the Directorate General for Hydrocarbons (DGH), and the National Gas Research Institute (NGRI) identified more than 88 potential drill sites.

Detailed review and ranking (criteria mentioned in Section 4 of this report) of all the sites (Table-1) was then conducted considering mainly the subsurface distribution of the gas hydrate stability conditions and the identification of 18 of the most prospective (primary) sites for drilling/coring/LWD/wireline logging during NGHP-02 in KG Basin. These sites were drilled as Sites NGHP-02-01, -02, -03 (Area E), Sites NGHP-02-5, -6, -7, -8, -9, (Area C) and Sites NGHP-02-14, -15, -16, -17, -18, -19, -20, -21, -22, -25 (Area B). In addition to the initially planned 18 sites to test 18 prospects, four more sites were identified during the course of the expedition to investigate the possible extension of identified gas hydrate reservoirs, resulting in a total of 22 sites that were investigated during NGHP-02 in KG Basin. The additional sites drilled to further delineate the identified prospects included Sites NGHP-02-04, -10, -24, -23.

3. Geological Setting of KG Basin

All three study areas are located off the eastern coast of India in the Krishna Godavari (KG) Basin (Figure 1) which is a typical passive margin modified by multiple episodes of sea-level change. The first marine transgression began during the Albian-Aptian time (*Bastia, 2007*) approximately 100 – 125 million years ago. The eastward tectonic tilt of the basin facilitated onset of the primary fluvial pathways (in the Godavari and Krishna areas) and the two present day delta systems which were established during early Miocene times (23 to 20 Ma). The structural pattern in the basin is typical of a passive margin with loading in shelfal areas, related phases of growth and extension, and formation of frontal toe thrusts. The normal/growth related listric faults (of Pliocene age) have a general NNE-SSW trend that conforms to the general strike of the margin and typically sole out in the shales below (*Prabhakar and Zutshi, 1993*).

Sediment input to the KG Basin is generally dominated by the Krishna and Godavari river systems (Figure 1). Both river systems have high sediment supply to the basin (*Bastia, 2007*). Additional sediment input to the basin from the north is related to the distal portions of the deep water turbidite fan of the Ganges-Brahmaputra River system, which drains much of the Himalayas. Further, (on-land) horst and graben structures have influenced the fluvial drainage system throughout the evolution of the margin to the present day. In general, both rivers have built substantial deltas so that sedimentation at the gas hydrate prospective areas is dominated by terrestrial river input (*Biksham and Subrahmanyam, 1988*).

Lithostratigraphic evaluation of well data suggests that “Godavari clay” is the Pliocene layer on stratigraphic section in the area *(DSN Raju, 1994*). This formation was deposited during the active delta progradation of both the Krishna and Godavari river systems during the Pliocene, when the stream energy dominated over wave energy. During this period, meandering distributary channels carved the offshore pro-delta mud and were ultimately plugged with suspended load clays. The sand packages in this area appear to be a part of the frontal splays of channel levee complexes deposited in the lower slope environment. The formation consists mainly of soft clay/claystone, silty and sandy claystone with intermittent medium to thin bedded channel fill sandstone. See *Collett et al., (this issue)* for further evaluation of the depositional systems for the shallow section within the study area. As a result, seismic profiles in the study area often show features related to deep-water fans, including cut and filled channels. Thus, the sediments are expected to be clay rich, but with well-defined sand horizons (*Sastri, et al., 1981*) in proximal environments, with the potential for more areally extensive fan systems in more distal environments.

4. Site Evaluation – process and criteria

The site evaluation process for NGHP-02 drilling builds on successful efforts in recent years to incorporate petroleum system concepts into the specific context of gas hydrate exploration *(Boswell et al., 2016*). The method primarily relies on recognizing the potential response of the reservoirs in each individual 3-D seismic dataset (typically a strong amplitude reflection of polarity similar to the seafloor) and mitigating the geologic risks inherent in such prospects through comprehensive evaluation of all relevant elements of the gas hydrate petroleum system, such as gas source, gas migration, and potential occurrence of suitable coarse-grained reservoirs *(Johnson and Smith, 2006; Collett et al., 2009; Max and Johnson, 2014*). This approach builds upon experience gained in gas hydrate exploration in Japan (*Saeki et al., 2008*) and was first developed and successfully employed in the selection of prospective drill sites in the Gulf of Mexico in 2009 (*Boswell et al., 2012*). Site evaluation criteria used in this study further builds upon this approach, which includes the following four primary elements as summarized (*Boswell al., 2016)*-

- *Establish the extent of the Gas Hydrate Stability Zone (GHSZ):* This requires mapping BSR occurrences to establish the likely position of the Base of Structure I Gas Hydrate Zone (BS_IGHZ) throughout the area of interest. Where a BSR is neither present or it is unclear, a general model for the BS_IGHZ is established, which is often based on calibration and correlation to other near-by areas where a BSR could be identified. The assessment of the extent of gas hydrate stability in each region is also verified by calculating the base of Structure I Gas Hydrate Stability (BS_IGHS) assuming a pure methane gas (as documented for NGHP-01 sites by *Lorenson et al., 2017*) and normal sea-water salinity as informed by local information on bottom-water temperature and geothermal gradient. No evidence of potential Structure II gas hydrates has been observed in any of the study areas.

- *Identifying evidence for gas sourcing and migration into the GHSZ:* It is expected the study area will be dominated by gas hydrate-I systems formed from deeper biogenic gas, not necessarily deeper thermogenic gas even if the delivery system may exist. Therefore this criterion requires an understanding of proxies for mechanisms of gas delivery into the GHSZ, which can take many forms, including:

- Chimney structures: the presence of such seismic features is taken as strong evidence of gas generation at depth and upward migration of gas into the GHSZ.
- BSRs: BSRs provide additional confirmation of gas sourcing from deeper sediments below the GHSZ that migrates upward into the gas hydrate stability zone.
- Enhanced reflections below the BSR: anomalous amplitudes of appropriate polarity (where polarity is clear) below the BSR are strong indicators of gas occurrence and deeper gas sourcing.
- Seafloor gas expulsion features and other seafloor expressions: such features as mounds and gas vents/seeps indicating active or recent gas flux through the GHSZ. Mapping of detailed seafloor topography provides evidence for gas migration through the GHSZ.

- *Evidence of sand reservoir facies within the GHSZ:* This element refines the site selection and evaluation process because gas hydrate in sand reservoirs is considered to be more suitable for gas production than gas hydrate in a shale or mud reservoir. Therefore, there is a deliberate search for evidence of the presence of sand reservoirs to host gas hydrate formation and accumulation; the important evidence for the presence of gas hydrate include the following:
  - Seismic facies: overall, sedimentary sections characterized by monotonous and laterally consistent seismic reflectors within intervals of laterally consistent thickness are thought to be less prospective for sand occurrence. In contrast, zones of strong lateral thickness variation, including potential cut-and-fill, or zones with generally more poorly organized internal reflections, are considered to have greater potential for sand occurrence (*Riedel et al., 2013*).

  - Paleogeography: Deep water sand deposition is enabled by sharp reductions in depositional gradient. In other regions, salt tectonics (*Frye et al., 2012*) and subduction related thrusting (*Egawa et al., 2013*) have produced such settings upon the continental slope. However, in the areas studied, the toe of the slope is the most favorable location for the occurrence of sand.

  - BSR character: The expression of the BSR is controlled by many factors, both geological and related to the nature of the seismic data. However, BSRs, particularly where expressed not as a trough-going reflector, but as an alignment of anomalous seismic responses (*McConnell and Kendall, 2000*), is suggestive of a sedimentary section of variable permeability that is potentially more sand-prone (*Shedd et al., 2012; Boswell et al., 2016*).

- *Direct evidence of gas hydrate presence within the GHSZ:* Gas hydrate presence within sand-rich reservoirs is the key aspect in site identification and evaluation. This can be inferred from the following seismic evidence:

  - Elevated interval velocity: Identification of areas of interpreted elevated interval velocities may indicate the presence of gas hydrate at high saturation (see *Saeki et al., 2008*). However, reliable seismic derived velocity data are not available for the shallow sedimentary section of the NGHP-02 sites.

  - High amplitudes within the GHSZ: Strong amplitudes above the BSR are viewed as potential "direct" indicators of gas hydrate, particularly when (1) the amplitude is the same polarity as the sea-floor, (2) when the amplitude is organized in a manner that reflects control by local geologic structures, including anomalous terminations against faults and conformance to structural highs, (3) when the amplitude occurs in sediment packages that have seismic character suggestive of sand-prone depositional systems; and 4) when the amplitude occurs near the base of the GHSZ (high-amplitude, appropriate-phase reflectors can be generated by wet sands, particularly when encased in high-porosity, poorly-compacted, muds). High amplitude interpretation to distinguish between wet sand and gas hydrate is difficult though. However if polarity reversal at base of the GHSZ occurs, there is a possibility that high amplitudes are related to gas hydrate. In this study, a Root Mean Square (RMS) seismic amplitude strength analytical method was used to delineate gas hydrate accumulations and to infer the concentration of gas hydrate (Tamaki et al., 2017). The RMS value is an important measure to infer the energy in a waveform over a certain length of time. The anomalous peak value in instantaneous amplitude values gets averaged over the selected time window (often one waveform) therefore amplitude distributions from trace to trace are most likely smooth and minimize the effect of noises. This leads to better prediction of amplitude strength changes that are most likely related to lithological and elastic rock properties of gas hydrate. The geometrical shape of RMS amplitude distributions in a 3D seismic data volume often result in determining the nature of geological features and the depositional environment. Additionally, where amplitude changes are not conclusive, other attributes like the sum of positive or negative amplitudes can be utilized to ascertain the reservoir distribution pattern and limits.

  - Appropriate change in reflection character across the base of gas hydrate stability (BGHS): Prospective amplitude features within the gas hydrate stability zone (GHSZ) are very likely gas-hydrate driven where they can be observed to reverse polarity (indicative of transition from gas-hydrate-bearing sediment with elevated velocities to deeper free-gas-bearing sediment with lower relative velocities) where the strata can be traced across and below the

BGHS. Amplitude is also prospective where they change significantly across the BGHS without a polarity reversal (indicative of transition from gas-hydrate-bearing sediment to water-bearing sediment).

5. Krishna-Godavari Basin Seismic Data Analysis and Interpretation

Area of studies presented here are Area B, Area C, and Area E (Figure 1). Each area is covered by conventional marine streamer 3D seismic data. The available seismic data volumes have different polarity convention. Therefore, the following section describes the polarity convention of the seismic data volumes used for the present study.

Considerations of Data Phase and Polarity: The evaluation of gas hydrate occurrence from seismic data requires an initial understanding of the phase convention used in the data (*Boswell et al., 2016*). Phase is estimated through observation of the seafloor reflection character. Data for the three KG basin sites use a range of phase conventions (Figure 2), including North American 0^o Phase (where the seafloor is marked by a trough-strong peak-trough), “European” Phase (the seafloor is a peak-strong trough-peak), and North American -90^o Phase (the seafloor is a trough- peak). The phase convention dictates the expected response of gas-hydrate bearings sands as shown in Figure 2 and as follows: European (trough-over-peak), North American 0^o (gas-hydrate-sand is peak-over-trough); and North American -90^o (trough-peak).

Gas hydrate prospects in Area B (Vizag): Area B (Figure 1) is dominated by a large dome-like structure cored by Miocene shales and flanked by on-lapping younger syn-tectonic sediments with possible channel features in the north-north eastern quadrant of the dome. The dome structure in Area B is traversed by a strong BSR that clearly cross-cuts the stratigraphy (Figure 3). Mapped amplitudes suggest possible linear and lobate geobodies associated with channel – levees that may be indicative of sand-rich systems. Twelve sites were ultimately drilled in Area B, testing multiple horizons in a variety of geologic settings.

One primary target in Area B is a high amplitude (peak-over strong trough) event (R1) that is prospective for gas hydrate (Figure 3, and in data of reverse phase in Figure 4). Across the crest of the structure, the R1 event occurs well above the BSR, and locally appears to exhibit strong amplitude changes associated with faults (Figure 4). In the down-dip position, the R1 reflector is characterized by a complex interaction as it crosses the BSR at a relatively low angle (Figure 3). The high amplitudes at the BSR suggest locally elevated saturations of free gas. However, below the BSR, the seismic response of the event is less clear. An RMS amplitude map draped over a time-depth surface reveals a potential channel morphology in the north-northeastern quadrant of the area (Figure 5). Many of the above properties suggest this reflection is moderately prospective for sand with potentially high gas hydrate saturations and with gas trapped in the down dip position. Prospectivity of the R1 target is moderated by the lack of a clear change in amplitude response below the gas hydrate stability zone.

A second prospective reflector in Area B is designated as R2. In the down dip lines (Figure 3 and 4), the R2 event is clearly imaged below the BGHS as an amplitude event of polarity matching the seafloor. As the event is traced up-dip, it is observed to impinge upon the BGHS at which point the seismic response changes character and increases substantially in magnitude (Figure 6). The strong amplitudes and marked change in amplitude response across the BGHS make this event highly prospective for gas hydrate occurrence. Seismic amplitude (RMS) extracted within a 40 ms (TWT) window from the R2 event is displayed on a time (TWT) structure contour map in Figure 7. This feature where it is most prospective for gas hydrate was the primary target for 4 proposed sites (Sites NGHP-02-16, -17, -20, and -24), each of which was designed to test an individual fault block (Figure 8). Site NGHP-02-23 was identified as an additional site onboard during the expedition based on of the analysis of LWD data from Sites NGHP-02-17 and NGHP-02-16.

Gas hydrate prospects in Area C (Godavari): Area C comprises a single large depositional system exhibiting evidence of channelized deposits transitioning down dip into complex sequences of stacked fans (*Collett et al., this issue*). As with Area B, mapping of key seismic horizons in Area C was also carried out to locate sand bodies prospective of hosting gas hydrate at high saturations. Mapped amplitudes suggest possible linear and lobate like geobodies usually associated with channel – levees that may be indicative of sand-rich systems. Six prospective sites were identified in Area C. Four sites (that were later drilled as Sites NGHP-02-07, -08, -09, and -10) lie in the northwestern part of Area C and two sites (Sites NGHP-02-05, and -6) are located in the southeastern part of Area C (see Figure 1). A seismic section passing through the prospective sites in the northern region is shown in Figure 9. While the BGHS is not clearly imaged at this site, it is inferred that the more distal prospective sites (that were later drilled as Sites NGHP-02-08 and -09) occur close to the BGHS whereas the more proximal targets (Sites NGHP-02-07 and -10) are positioned well above the BGHS. The surfaces mapped along the primary seismic horizon targeted at the distal sites are used to extract RMS amplitude (40 ms below horizon) as displayed on a TWT structure relief map (Figure 10). This amplitude shows a pervasive, but heterogeneous positive impedance response.

Two primary sites (later drilled as Sites NGHP-02-05 and -06) were identified in the southeastern, deep-water part of Area C (Figure 1). These primary sites are located on broad anticlinal highs separated by a well-defined low (Figure 11). At both sites, intervals of high amplitude reflectors are correlative to the prospective interval identified in the shallow water sites. The high amplitudes are largely restricted to the inferred GHSZ and are observed to change markedly in amplitude character across the inferred BS_IGHSZ. The deeper target zone at Site NGHP-02-05 exhibits alternating positive and negative seismic amplitudes (likely to reflect multiple stacked sand units) that show a change in reflection character as they are traced below the base of the GHSZ (Figure 12). The target horizon mapped at Site NGHP-02-05 was used to extract RMS amplitude (high positive) within a 40 ms window (Figure 13) that shows an extensive, but highly heterogeneous distribution with some indication of lineation in the downslope direction. At site NGHP-02-06, an additional target at a shallower level is suggested by a locally high positive amplitude occurrence within the GHSZ, however, the polarity of that event is less prospective given the phase of the data (Figure 14). A seismic attribute map for Site NGHP-02-06 is provided (Figure 15). At both sites (NGP-02-05 and 06), the amplitude distribution suggests that the prospective, high-amplitude interval may be bounded/controlled by faults.

Gas hydrate prospects in Area E (Krishna): Area E lies in the Krishna-Godavari Basin where water depth ranges between 1400 to 2000 m. Only one site was tested in Area E during NGHP-01 (Collett et al., 2014); however, the area features several prospective attributes, including high amplitude events above the BSR, a variable manifestation of the BSR, and indications of gas charge below the BSR (Figure 16). Mapped amplitudes suggest possible linear and lobate geobodies that may be indicative of sand-rich systems (Figure 17). Four prospective sites were identified in Area E: the sites drilled as NGHP-02-01 and NGHP-02-04 are located in the more distal south-western part of Area E, whereas Site NGHP-02-03 is in the more proximal part of the study area (Figure 1). One site (Site NGHP-02-03) specifically targeted a seismically-imaged channel (Figure 18) that was prospective for hosting gas hydrate in a flanking proximal levee facies based on seismic amplitude response and distribution (Figure 19). It is also inferred from seismic mapping that the channel related reservoir system identified at Site NGHP-02-03 is likely genetically related to additional prospects further downslope. One such prospect was targeted by Site NGHP-02-02 (Figure 20). The horizon seismic amplitude (RMS) attribute extracted within 40 ms below the mapped horizon and displayed on structure map (Figure 21), indicates a likely sand prone area within the gas hydrate stability zone.

6. Krishna Godavari Basin Gas Hydrate Prospects

Several sites identified in the KG Basin were reviewed in detail based on the specific site selection criteria developed for identifying petroleum systems, gas hydrate deposits, and associated risks. The evidence observed from 3D seismic data allowed the mapping of specific geological (target) features and their interpretation in context of larger structural and depositional features. Out of 22 sites, 16 sites featured prominent BSRs that help confirm the depth to the base of the Structure I gas hydrate stability zone, thus mitigating the risk that the targets may be outside the GHSZ. At some sites (Sites NGHP-02-14, and -15), the BSR is either disrupted by local fluid migration from the deeper sediments or is not distinguishable (Sites NGHP-02-18 and -19) because the BSR is parallel to the regional stratigraphic layers. A synopsis of observations about the identified prospects is given in the previous section. The results of the drilling and the comparison to the pre-drill prospecting reported here are provided in full detail in *Shukla et al., (this issue)*. Based solely on the pre-drill seismic analysis, the NGHP-02 prospective targets are described as follows:

Area B: In Area B, two prospective gas hydrate targets were identified: an "upper" reservoir (R1) and a "lower" reservoir (R2). Both reservoir systems were likely deposited prior to the tectonic event that resulted in the broadly folded structure at the site. These reservoirs appear to have been locally folded into the gas hydrate stability zone, with both reservoir facies characterized by high amplitude events, although amplitudes observed associated with R2 were clearly stronger than those observed for R1.

The R1 prospect was the primary target for three sites (Sites NGHP-02-14, NGHP-02-15 and NGHP-02-22). These sites were located at the highest structural level and targeted high seismic amplitudes. The sites were also close to an interpreted fault that may have acted as a gas migration pathway. To characterize the gas hydrate distribution from crest to the flank along the observed anticline, and east of inferred fault, Site NGHP-02-21 was selected for drilling. For further delineation and extension of the R1 target, three sites (Sites NGHP-02-18, -19 and -25) were selected on the flanks of this elongated structure having high amplitude response close to (above) the BSR. Site NGHP-02-19 was selected and drilled (see *Kumar et al., this issue*) to test for the possible presence of an unconformity or other stratigraphic complications. Site NGHP-02-25 was drilled on the eastern side of Site NGHP-02-19 to provide information on the section below the BSR for non-gas hydrate-bearing sediment characterization.

Two primary sites were selected to test the R2 prospect (Sites NGHP-02-16 and -17) at locations on the crest of the anticline with the highest amplitudes. The amplitude distribution pattern linked to this reservoir indicates the possible presence of highly-saturated and fault-compartmentalized gas hydrate deposits. Three additional Area B sites were identified during the course of the NGHP-02 expedition to further confirm and delineate the R2 section. One site (Site NGHP-02-23) was located between Sites NGHP-02-16 and NGHP-02-17. A second site (Site NGHP-02-20) was identified to confirm the extension of the R2 unit to the east of Site NGHP-02-16 in a structurally-higher fault block. A third site (Site NGHP-02-24) was also drilled to further extend the evaluation of R2 at a structurally higher level to the north-east of Site NGHP-02-20.

Area C: Sites in Area C were identified to test prominent interpreted channel features and associated sand-rich levees within a large deep-water channel-fan system. Several channel-fill sequences at mid and down-slope positions inferred from seismic data were prospective targets for thick sand reservoirs containing gas hydrate. Sites NGHP-02-07 and NGHP-02-10 were identified to test the channel-levee system in a mid-slope position that suggested greater prospectivity for channel/levee facies. Further down dip, two sites (Sites NGHP-02-08 and NGHP-02-09) were similarly located to test the sand-rich levee systems with concentrated gas hydrate saturations as inferred from seismic features. Finally, two sites (Sites NGHP-02-05 and NGHP-02-06) were identified to test a thicker section of potentially stacked fan sequences in a more distal setting based on thick packages of high-amplitude events.

Area E: Sites NGHP-02-01 and NGHP-02-04 were located in a channel-like feature above a strong and distinctive BSR. Further in this area, two sites (Sites NGHP-02-02 and NGHP-02-03) were identified upslope from site NGHP-02-01 to test the continuity and extent of a channel fill sand-rich gas hydrate system. Site NGHP-02-02 was positioned on the flank of the structure, designed to target potential stacked on-lapping fan deposits containing a high amplitude package of reflectors above a well-developed BSR.

7. Summary

The effort to identify prospective sites within the broader deep-water Krishna-Godavari Basin reflected the shift in the NGHP gas hydrate exploration strategies to search for deep-water sands within the gas hydrate stability zone that show evidence of gas charge. This evidence includes high seismic amplitudes of polarity that suggest increased impedance response that is consistent with gas hydrate occurrence. However, such amplitudes are not conclusive of gas hydrate occurrences, so full assessment of all the key elements of the petroleum system was conducted to further de-risk the prospects. This assessment includes evaluation of the presence of gas hydrate stability conditions, as well as evidence for the occurrence of sand-rich facies and for gas charge to the hydrate stability zone (*Collett et al., 2009; Boswell et al., 2016*).

The pre-dill/onboard assessment of seismic data yielded identification of 22 gas hydrate prospective sites in the KG Basin. This paper focuses on 17 prospects identified in three areas, 9 in Area B (Vizag), 5 in Area C (Godavari), and 3 in Area E (Krishna) that were eventually investigated and evaluated by 22 LWD borehole sites. The pre-drill studies provided a full list of highly-prospective sites that were invaluable to the success of NGHP-02. The results of the drilling (see *Collett et al., this issue; Shukla et al., this issue*) provided further validation to the developing gas hydrate prospecting approach, and contributed directly to the discovery of two prominent sand-rich gas hydrate accumulations that are currently under evaluation for potential field production testing (See *Myshakin et al, this issue; Moridis et al., this issue*).

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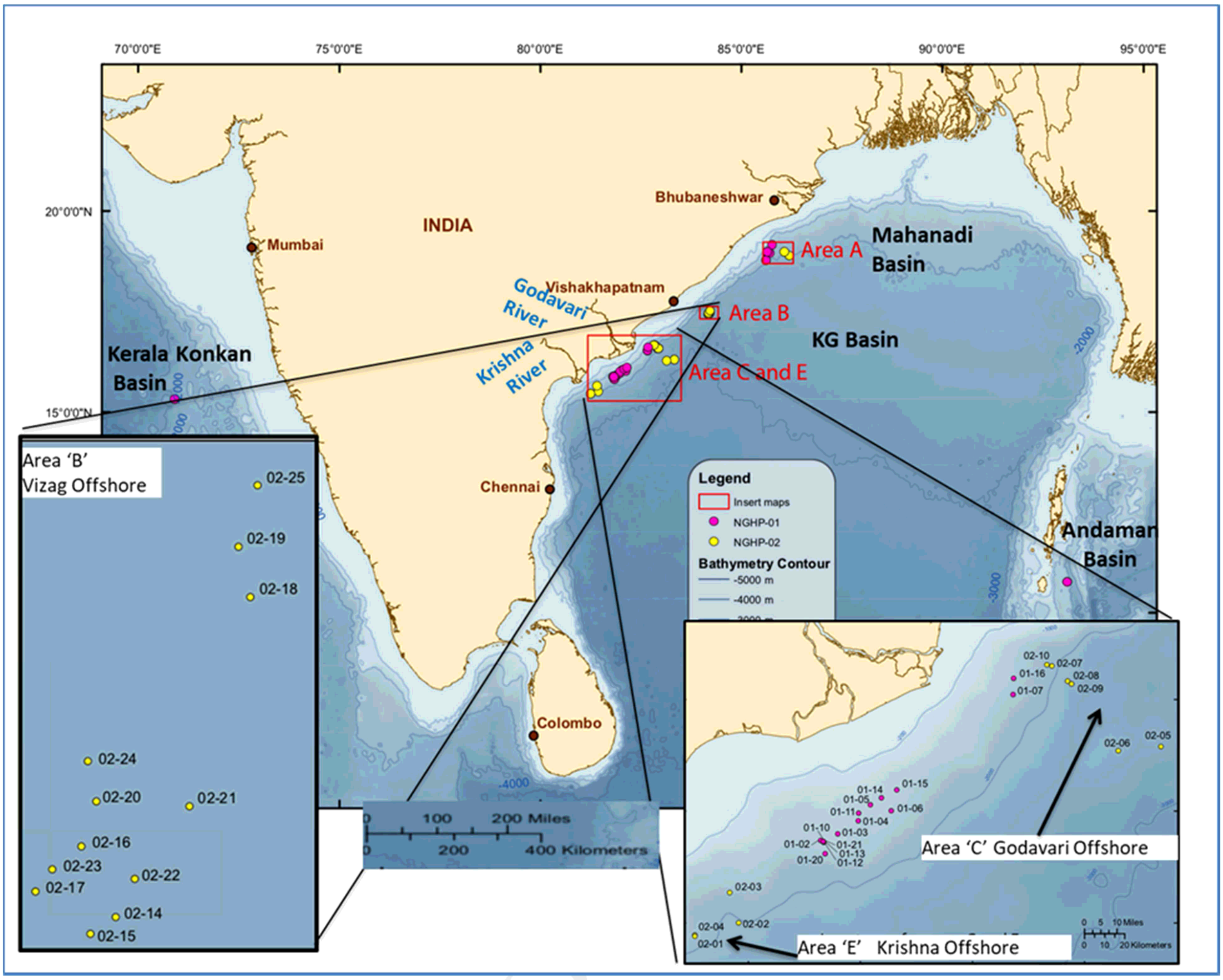

Figure 1: Index map showing geographic location of operational areas undrertaken during NGHP-02. Three prospective areas covered in KG Basin include Areas B (Vizag) -12 sites, C (Godavari) - 6 sites, E (Krishna) - 4 sites and Area A (Mahanadi) - 3 sites in the Mahanadi Basin. All NGHP-02 sites are shown by yellow circles.

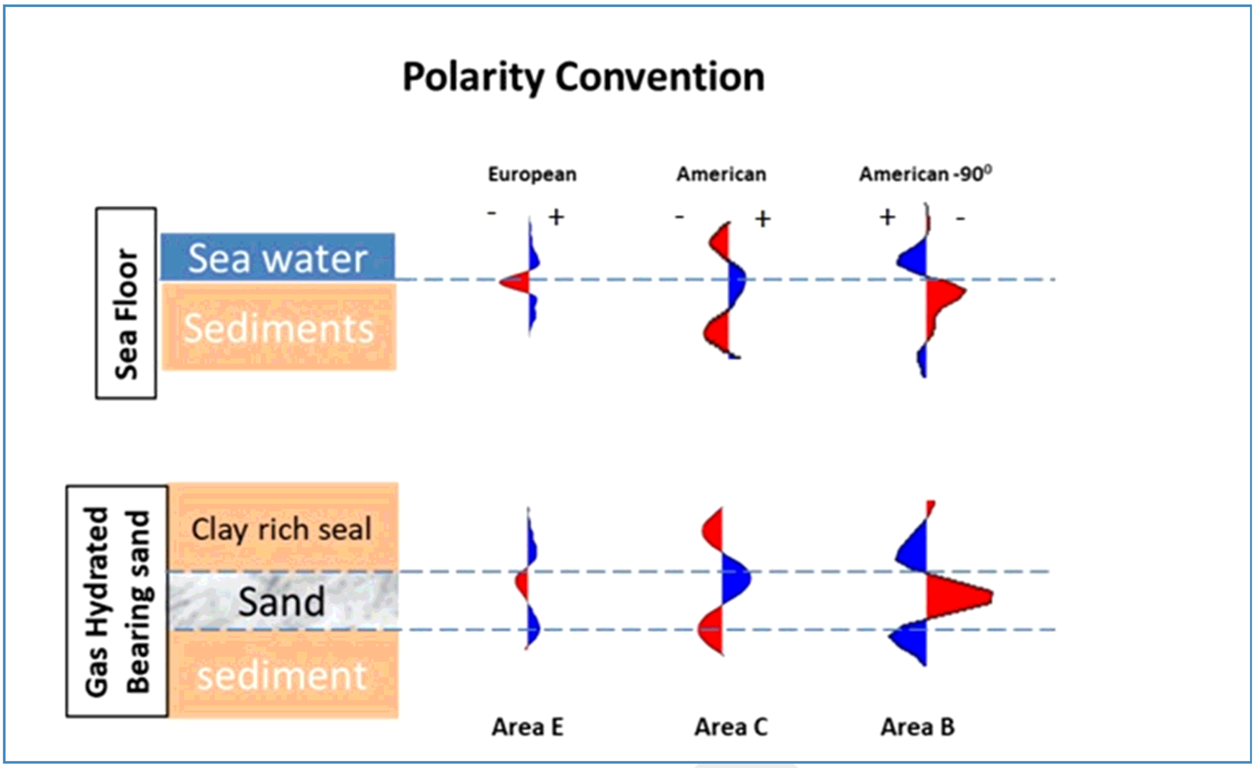

Figure 2: Seismic data evaluated included a range of data polarity conventions, which result in different seismic signatures for the sea-floor (Upper) and for prospective gas hydrate reservoirs (lower). Polarity convention for the seafloor and top of gas hydrate bearing sand is almost similar. Polarity convention shown here is extracted from seismic data evaluated for this study.

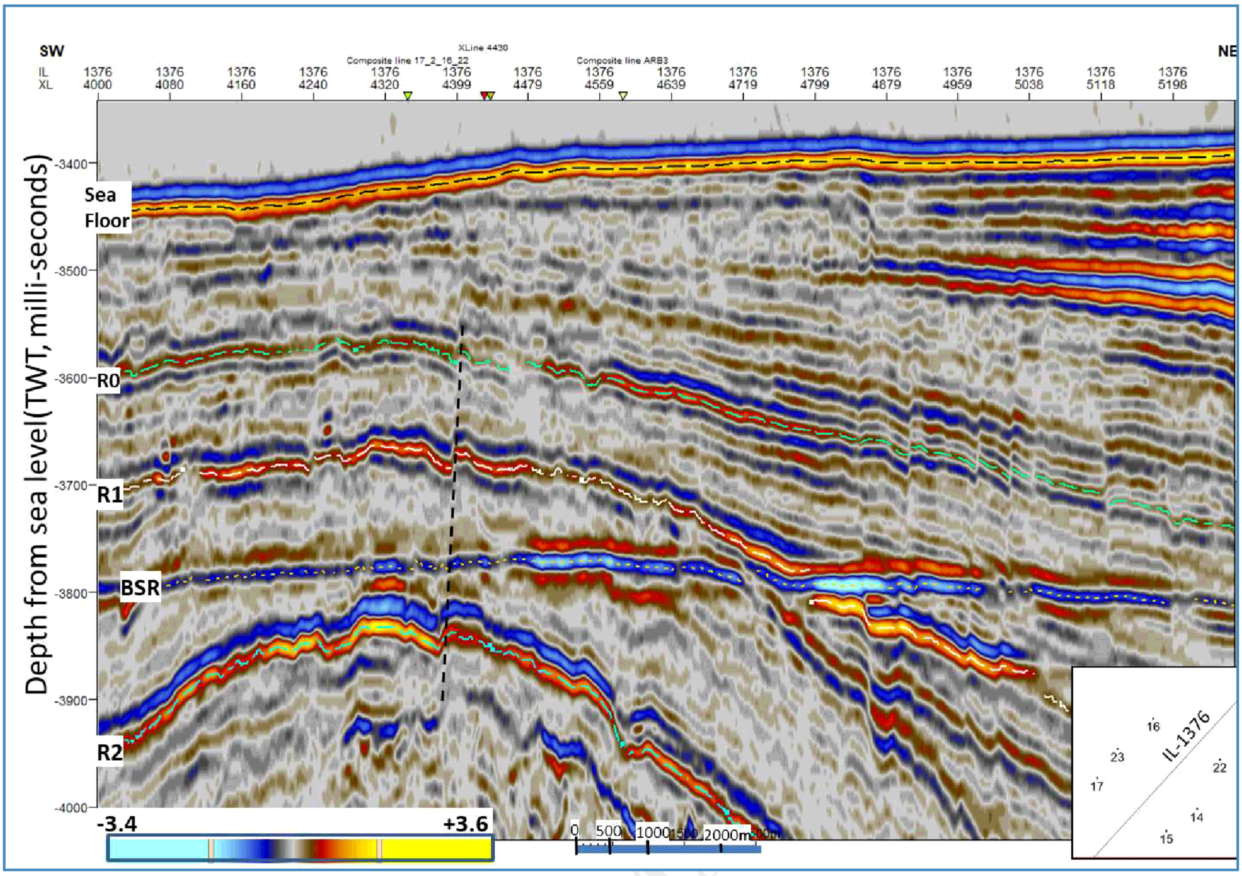

Figure 3. Seismic cross section (shown in inset as IL1376 relative to sites drilled in this region) in Area B showing the BSR marking the base of structure I gas hydrate stability and marker horizons R0 and R1 within the gas hydrate stability zone and horizon R2 below the gas hydrate stability zone. Amplitude color scale shown (Lower-left corner) is the same for other seismic sections for Area B.

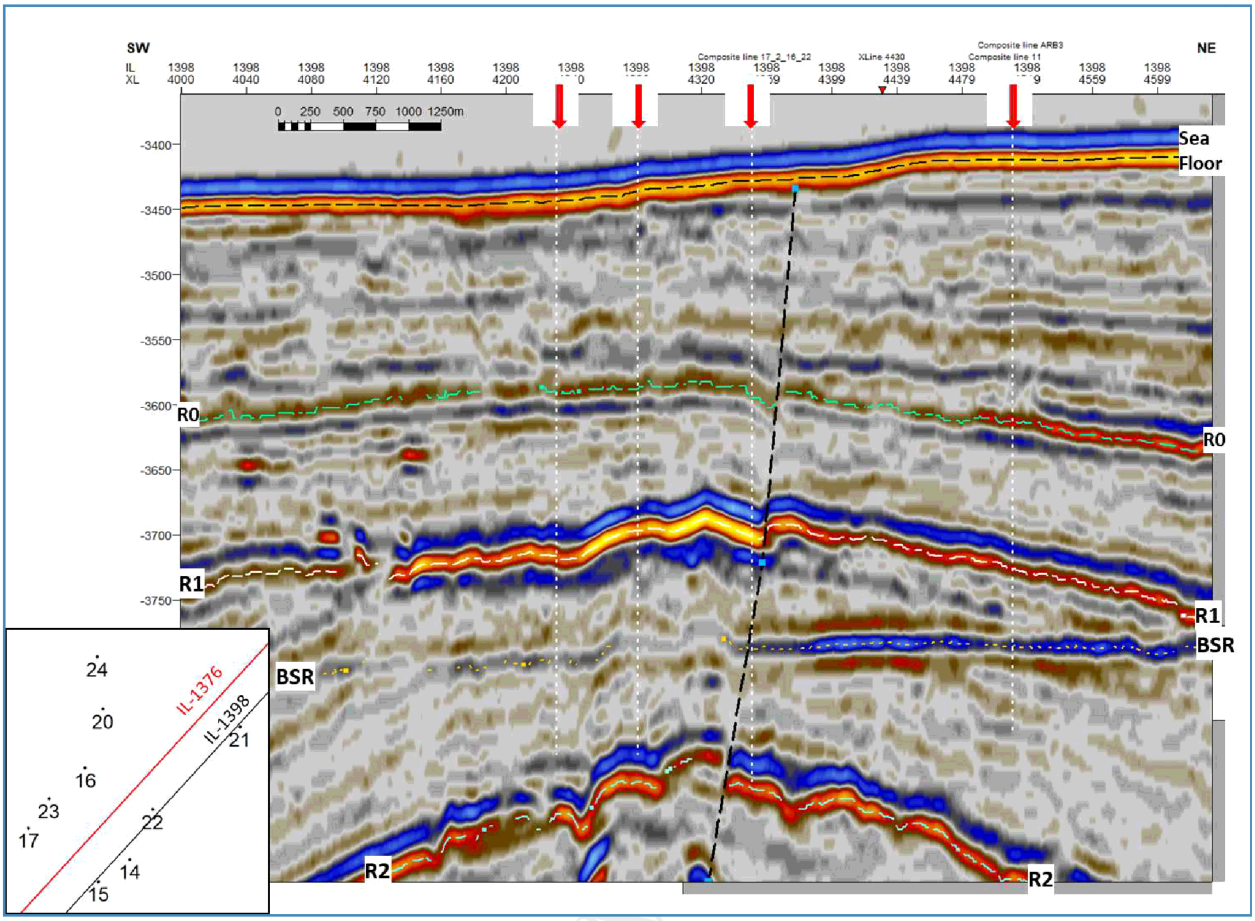

Figure 4: Area B seismic data (North American -90^{o} phase, shown in inset relative to the drill sites in the region as IL-1398) showing character of the R1 target above the base of gas hydrate stability, its apparent amplitude augmentation associated with a fault (black dashed curve). Arrows (red) showing the position of sites identified to test the amplitude strength likely to be related with gas hydrate saturation across the fault line. White dash line is showing well trajectories passing through Target R1.

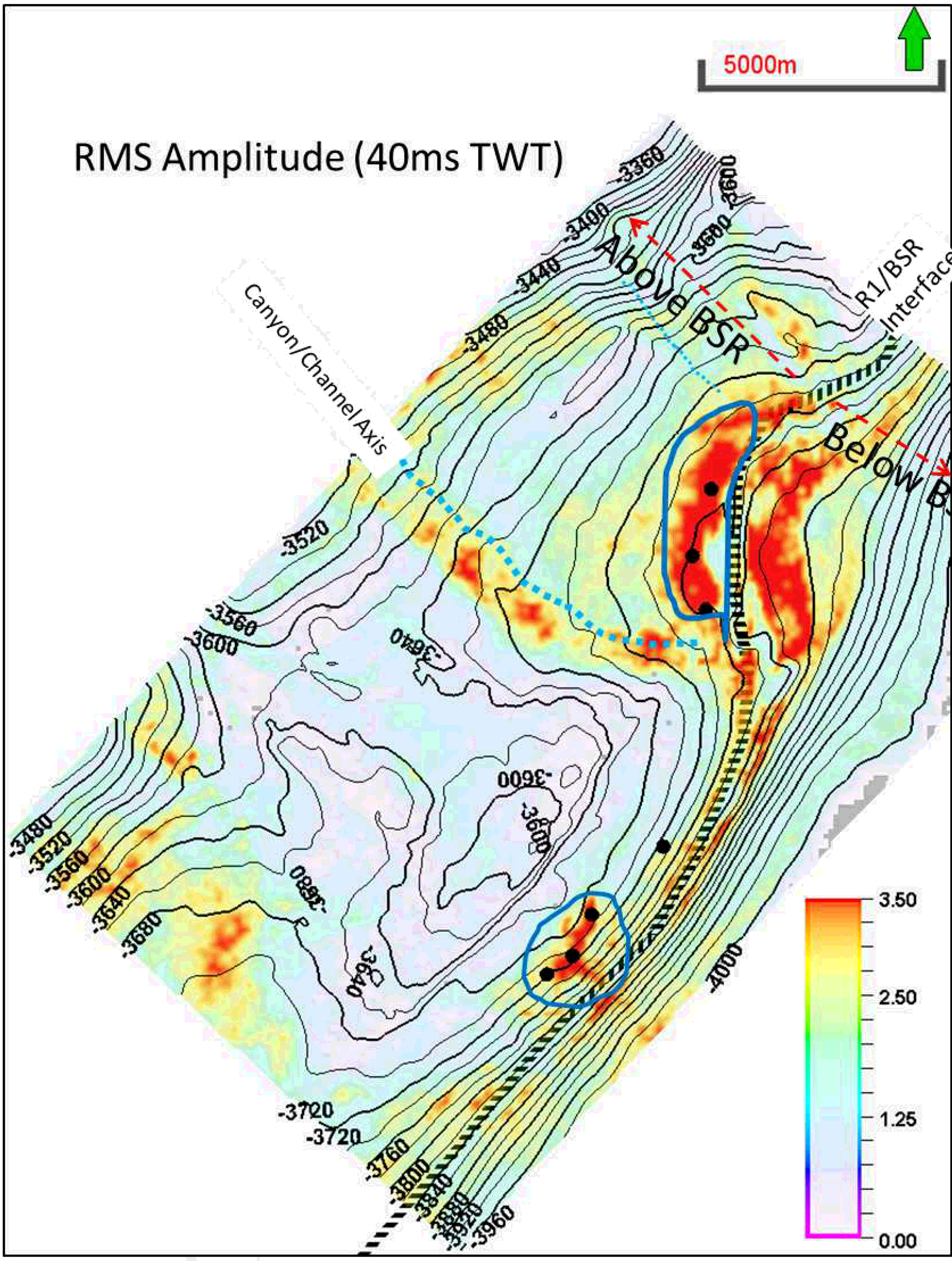

Figure 5: Surface RMS amplitude map for event "R1" (Figure 3 and 4) draped over two-way-time structure. A potential channel morphology that tracks a minor synclinal axis is noted trending WNW-ESE across the structure. Blue polygons show upper band of the amplitude attribute likely linked to channel related levees/fan hosting gas hydrate identified for testing at 7 sites (black dots). A minor canyon / channel axis inferred is shown as blue dash line based on local low. Black tagged line shows the interface depth (TWT) line where the R1 surface meets with the BSR. Color scale shows the attribute color range with adapted transparency to highlight the upper band of seismic amplitude (interpreted as sand prone areas). High amplitude anomalies above the BSR (interface) are likely to be gas hydrate rich. Green arrow is showing North direction.

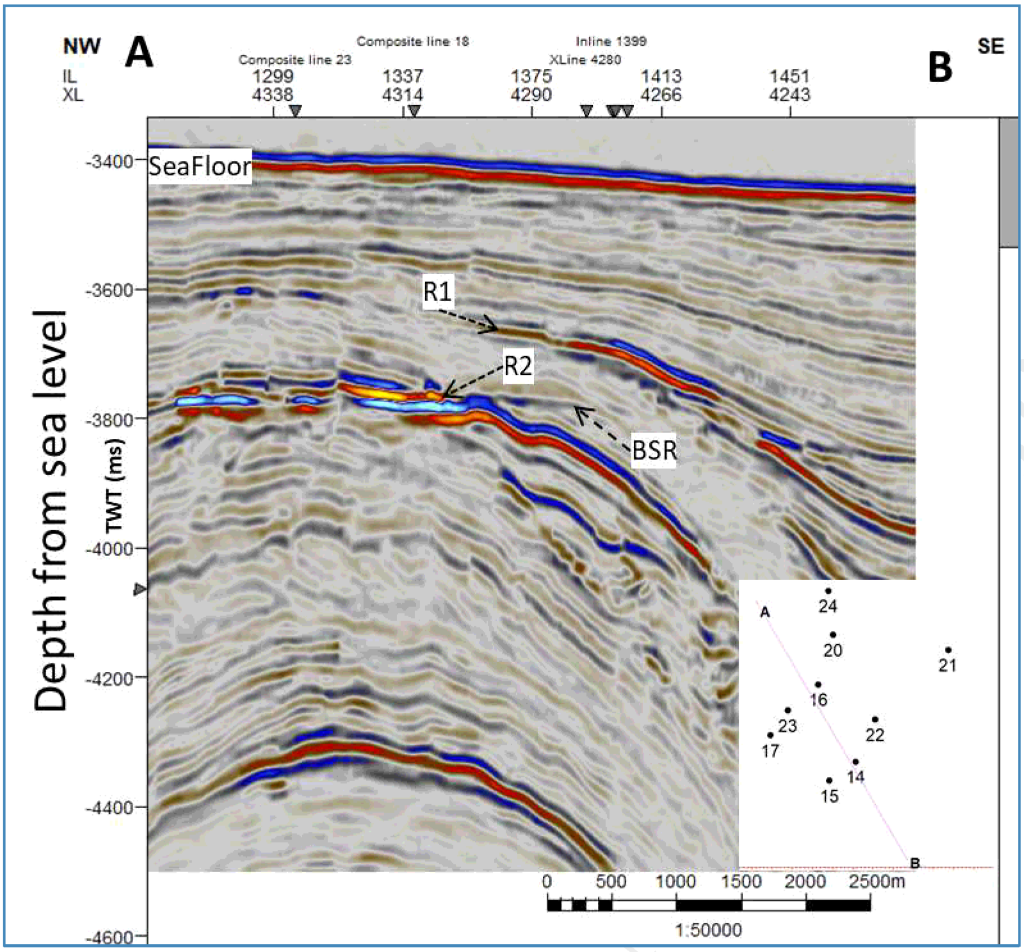

Figure 6. Nature of the R2 reservoir response in Area B. The event shows a range of seismic responses, including strong trough-leading event on the west flank of the structure near 'A' (likely indicating free gas); complex peak-trough-peak at the structural crest (prospective of gas hydrate), and less strong peak-trough on the eastern flank below the inferred base of gas hydrate stability (inferred water-bearing sand). This configuration suggests a potential sand unit that hosts pore filling gas hydrate in discrete segments due to its structural position and fault based compartmentalization. Data phase is North American -90^{o}.

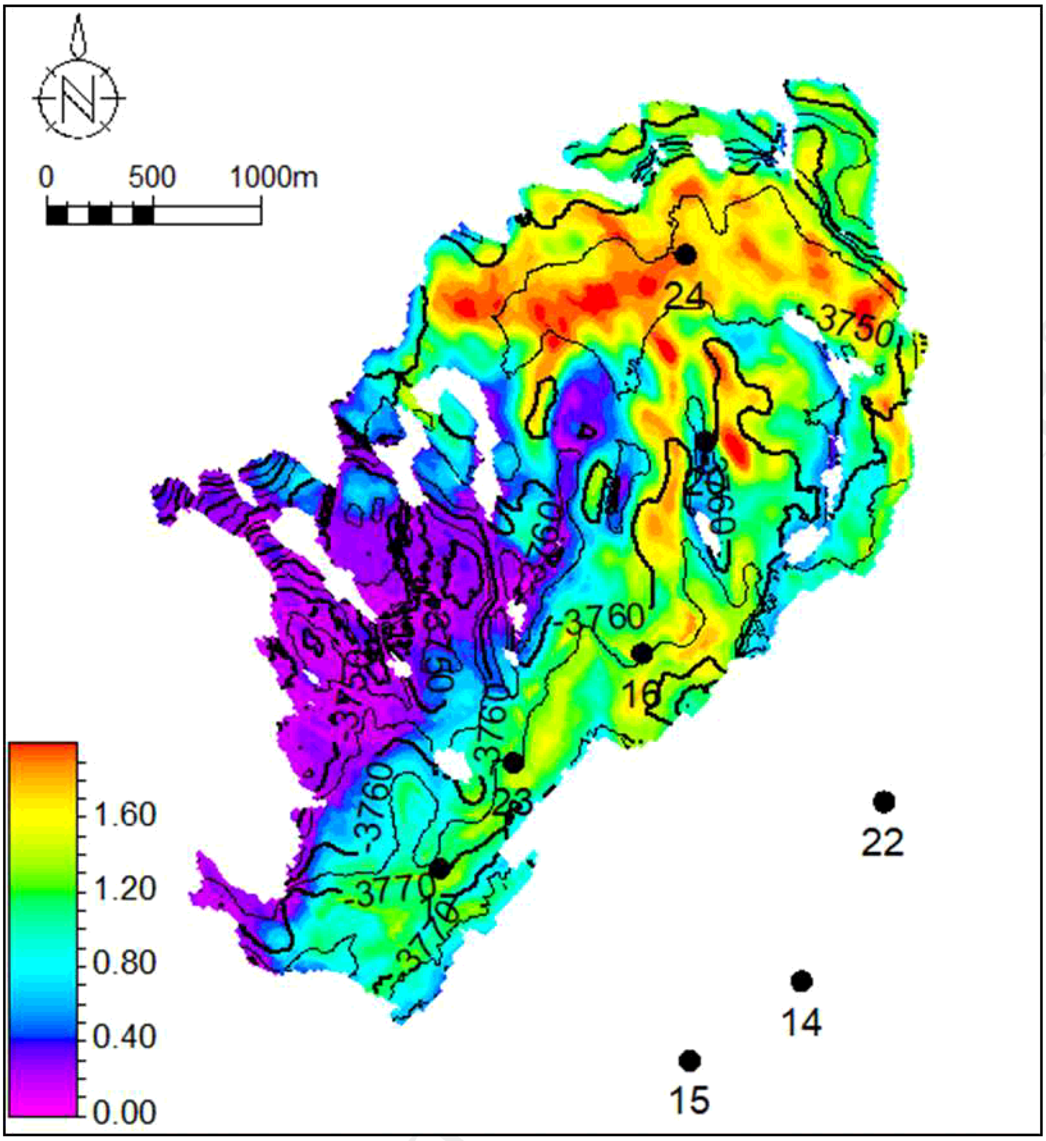

Figure 7: Amplitude (RMS) in a 40 ms window below R2 is extracted from the 3D seismic volume and shown with two-way travel time contours (in milliseconds). Red color indicates strong positive amplitude. Five sites for NGHP-02 (Sites NGHP-02-16, -17, -20, -23 and -25) were identified to test the gas hydrate potential of this (R2) prospect.

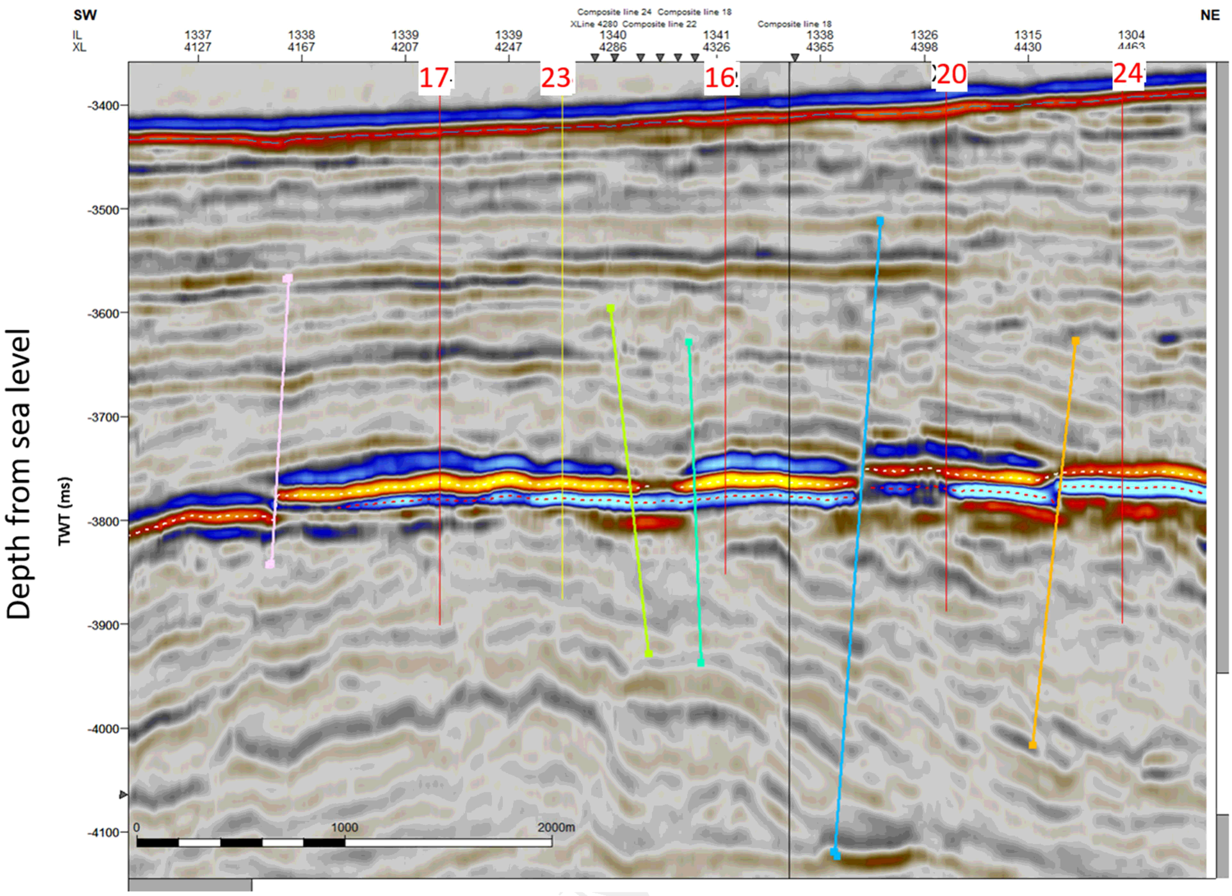

Figure 8: Seismic line through Area B showing the inferred fault (colored vertical lines with square tip) compartmentalization of the R2 reservoir and the approximate location of wells (vertical red lines) designed to test the most prospective areas of the accumulation. Depth is in TWT (ms). Red vertical lines are position where initially sites 16, 17, 20 and 24 were identified to test each compartments bounded by faults. Yellow vertical lines where site 23 was selected onboard during NGHP-02 operation.

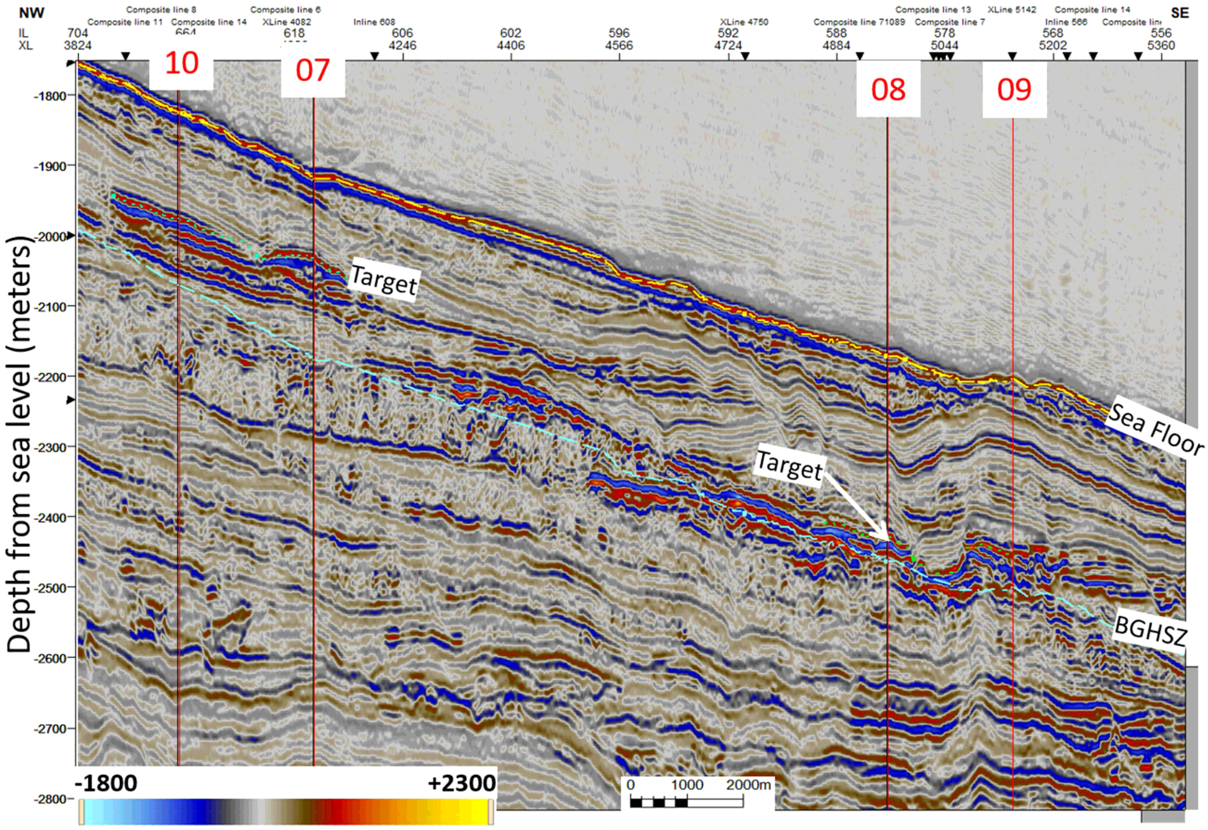

Figure 9: Seismic cross section A-B (fig.10) passing through four multiple prospective sites of NGHP-02 (10, 07, 08 and 09) in Area C. The seismic facies and strong amplitudes indicate high potential for sand-rich deposition. NGHP-02-10 was identified onboard during NGHP-02 operation. BGHSZ (Base of Gas hydrate stability Zone) is computed at sites assuming Seabed Temp. = 7 (deg. C) and Geothermal Gradient = 4.1 (C/100m), then it is interpolated using seafloor depth as guiding parameter.

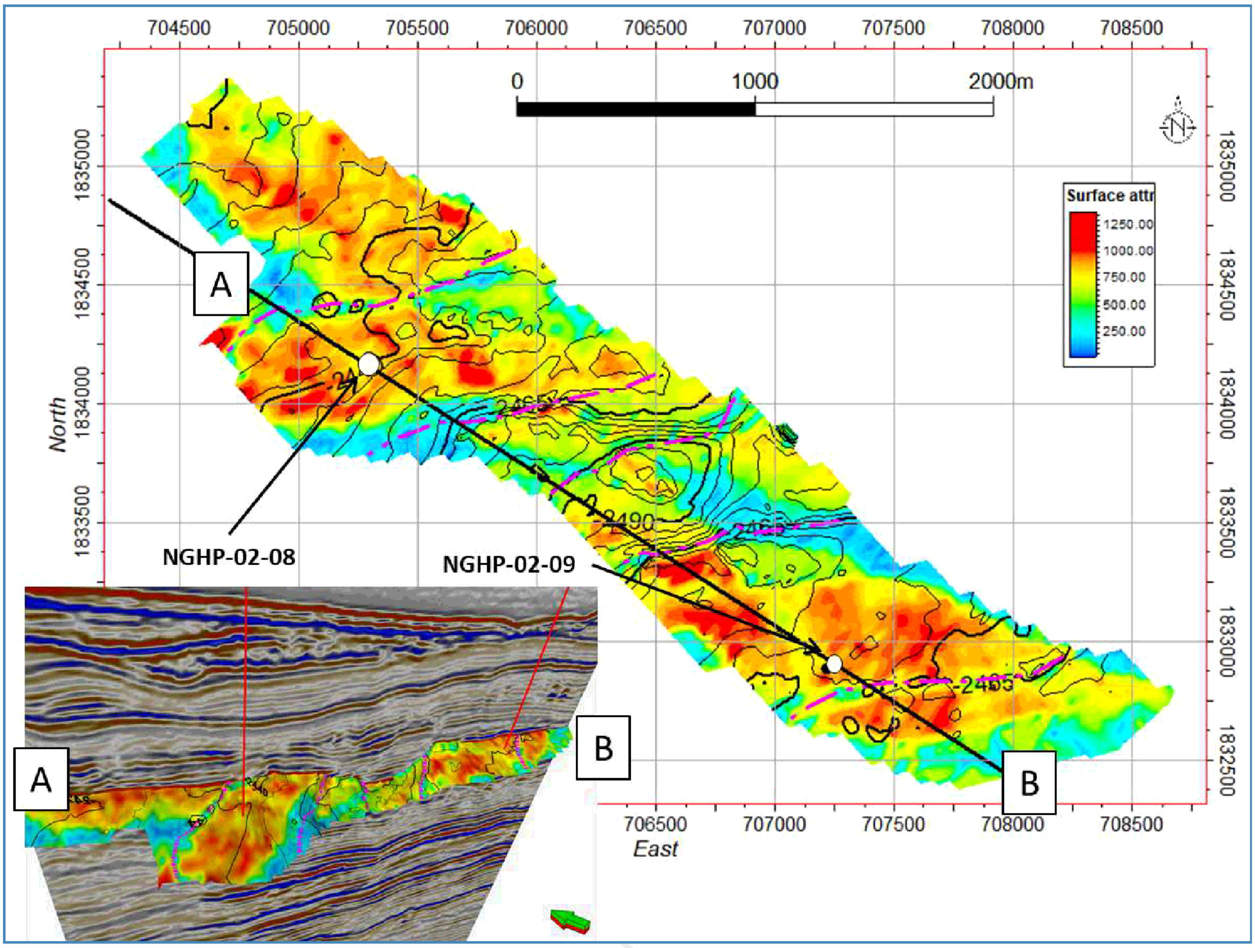

Figure 10: Structural perspective of the distribution of RMS amplitudes along the target horizon for Sites drilled as NGHP-02-08 and NGHP-02-09. Red color highlights the positive amplitude events interpreted to reflect sand containing gas hydrate at high saturation. High amplitude areas are inferred to represent flanking sand-rich levees around a central sand-poor channel axis. Position of minor local channel axis is indicated (pink dashed lines). Inset shows 3D structural perspective of channel levee complex identified along an arbitrary seismic line A-B.

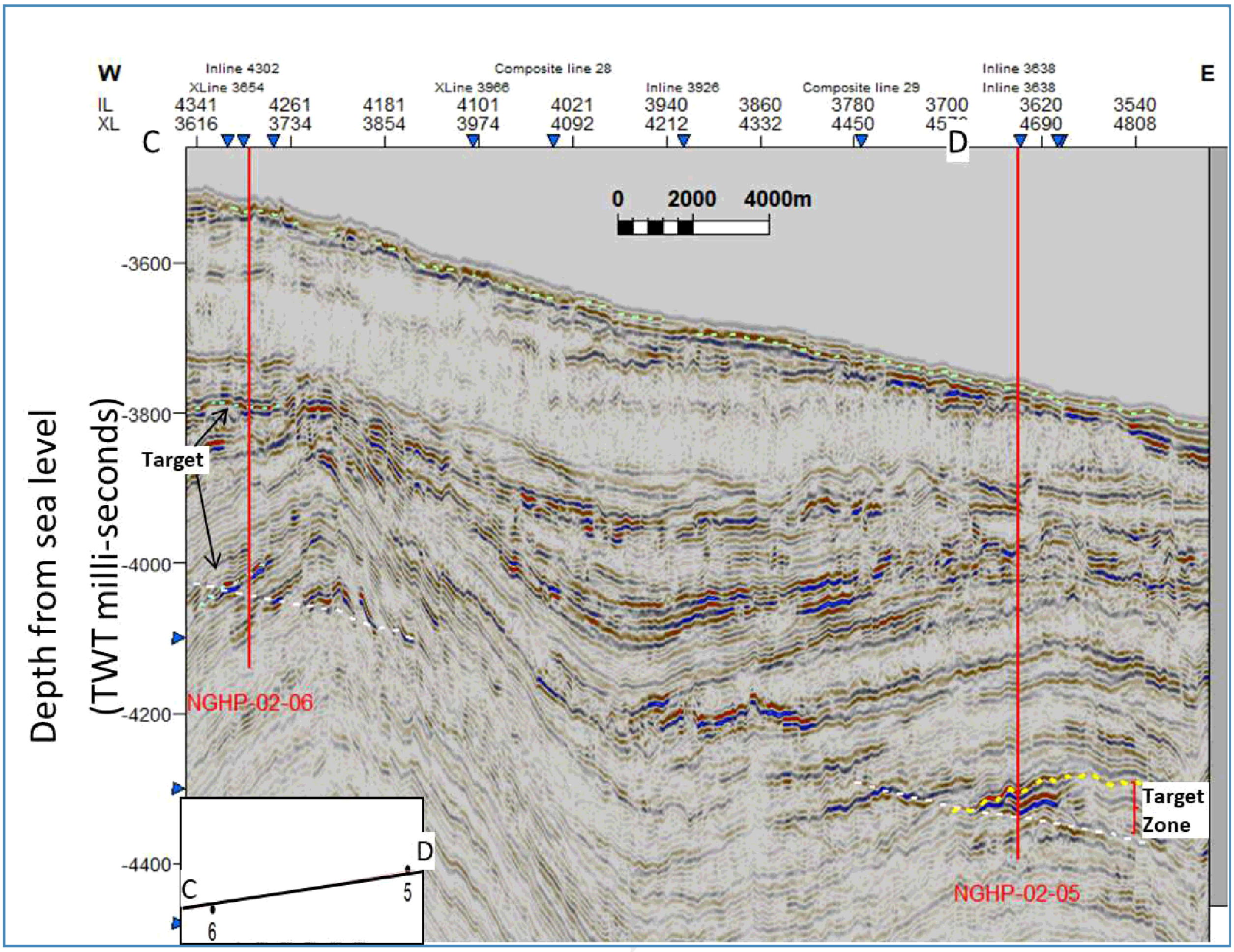

Figure 11: Regional view of a seismic cross section C-D passing through Sites NGHP-02-05 and NGHP-02-06 in the southeastern, deepest water region of Area C. The BGHS (white dash line) is not well imaged in the area as a through-going reflector but is inferred from the anomalous termination of high amplitude events as shown in Figures 12 and 13. Lack of amplitudes below the inferred BGHS suggest little to no free gas accumulations are associated with the target sections.

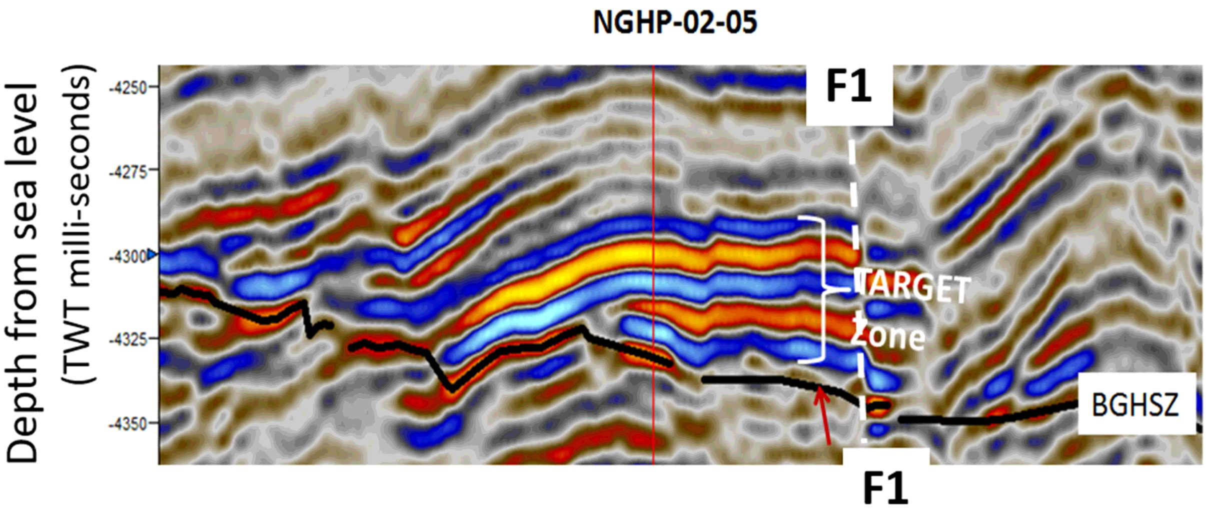

Figure 12: Zoomed view of Seismic cross section at NGHP-02-05. A strong positive reflection is observed to terminate at the inferred BGHSZ (black line) to the left and along potential faults F1 (white dashed line) to the right.

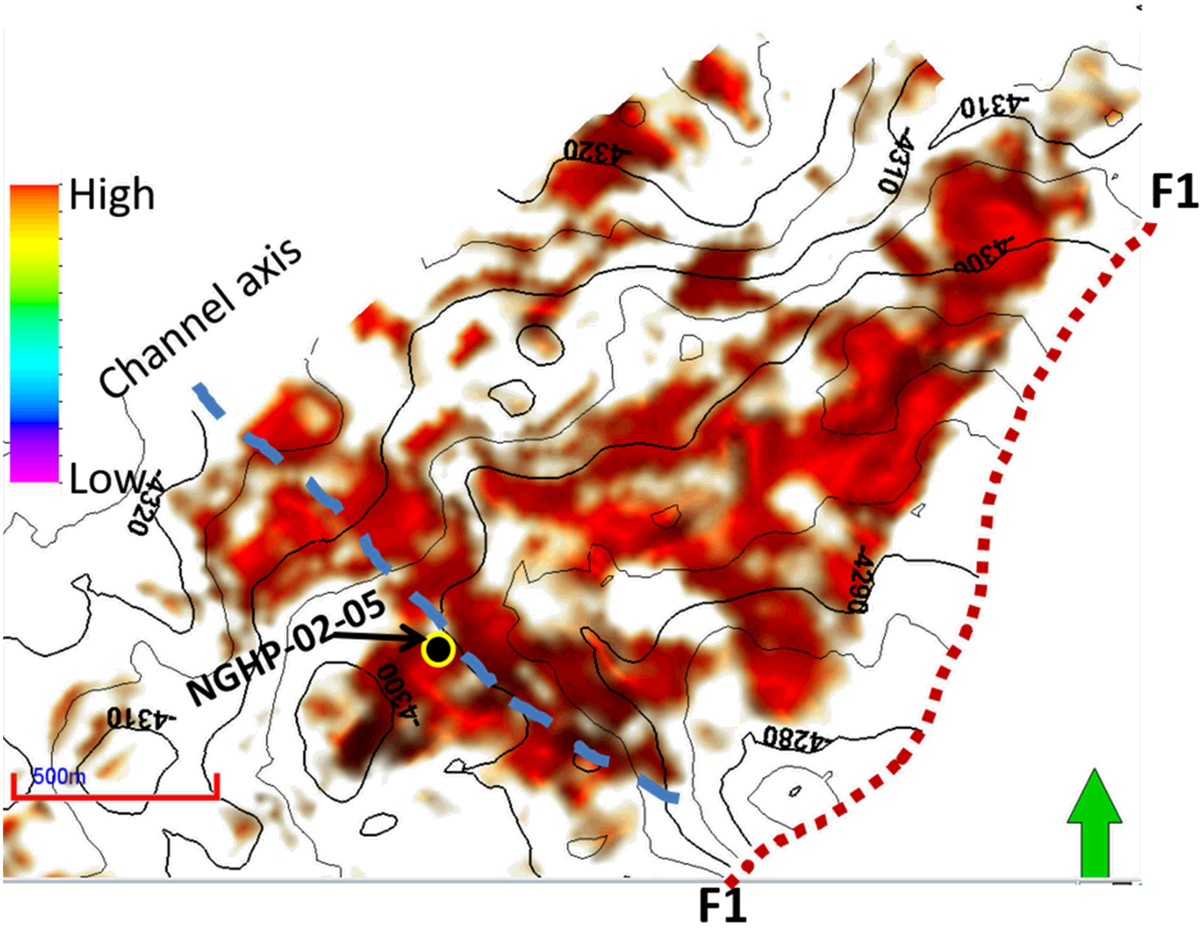

Figure 13. Structural perspective of the RMS amplitude (below 40ms window) attribute distribution for the target horizon at Site NGHP-02-05 (black filled yellow circle) in the southeastern part of Area C. Contour interval is 5 ms (TWT). The well site located on the western flank of inferred channel (Blue dashed line). Green Arrow pointing to the North direction. An opacity filter used to show only the distribution of upper band high amplitudes prominently. Fault F1 (Red dash line) shown in fig.12 (white dash line) is the probable eastern limit of prospect.

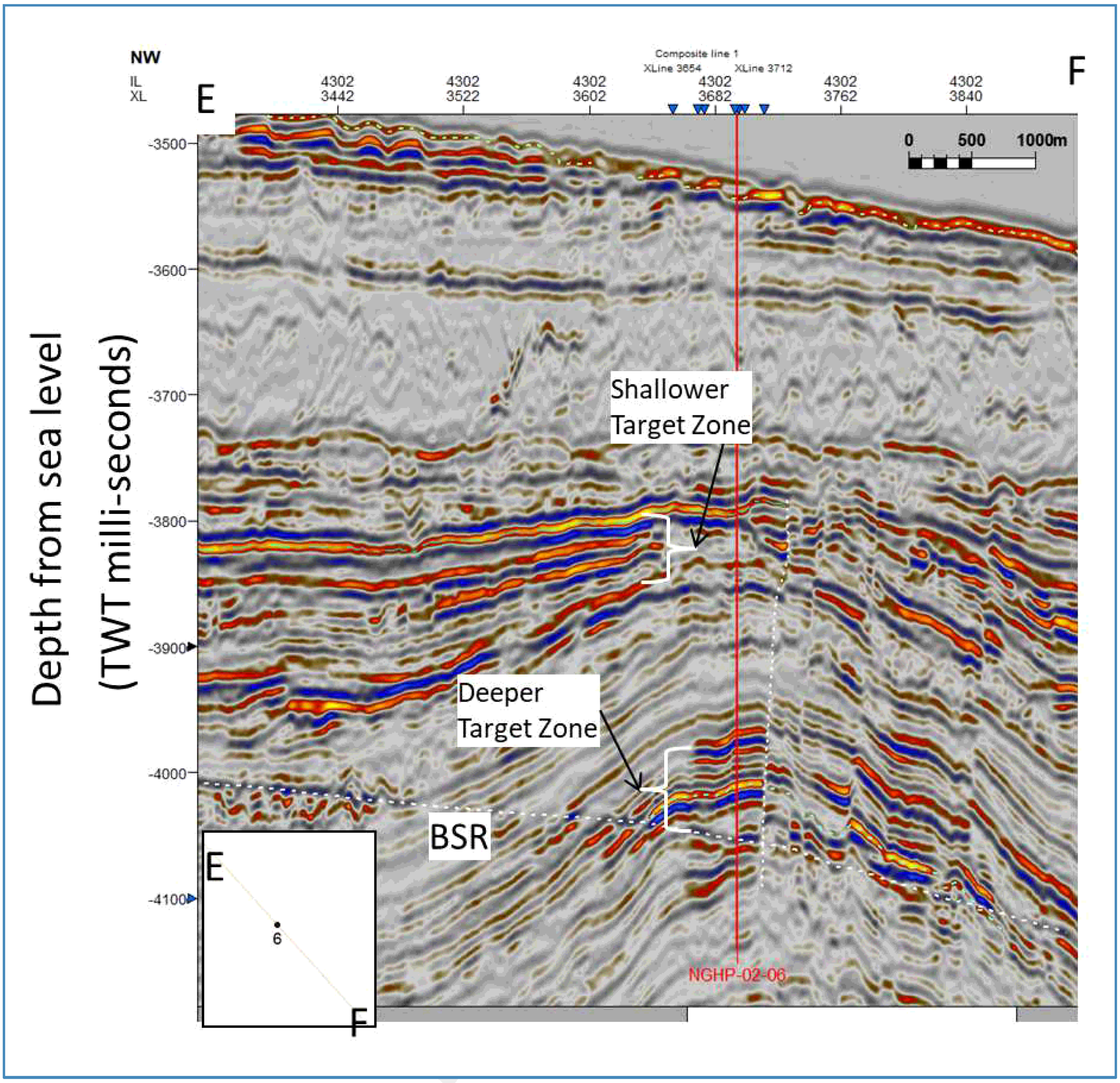

Figure 14: Zoomed view of seismic cross section at the Site NGHP-02-06 shows two targets. The shallow target shows reversed polarity from what might be expected for a hydrate bearing sand given the data phase. The deeper section shows bright amplitudes that appear to diminish at the inferred BGHSZ on the left and against a local discontinuity (near-vertical white dashed line) on the center of the structure. Light green dashed line within deeper target is the mapped reflector for attribute analysis (Fig.15).

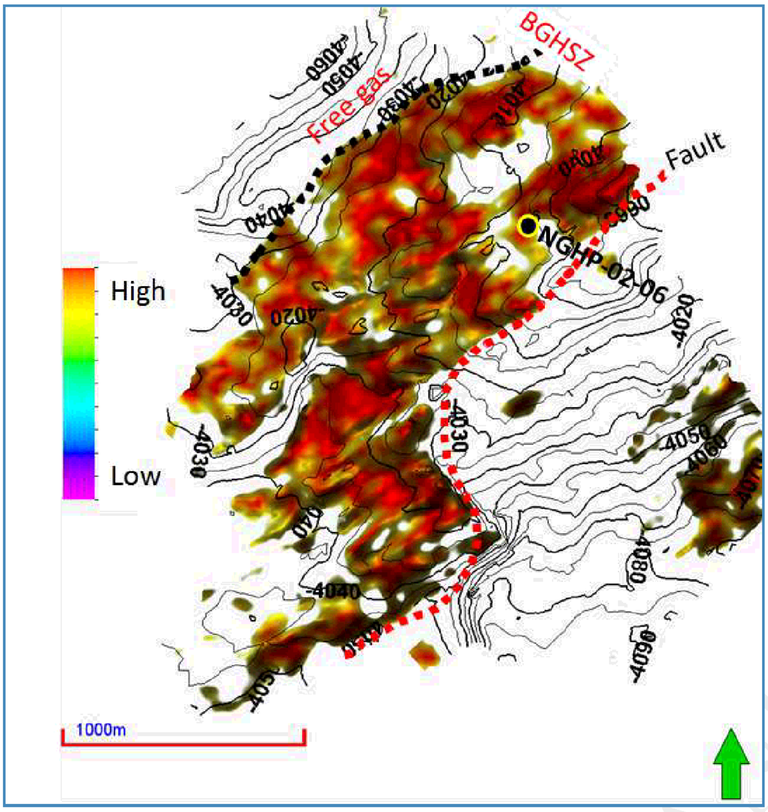

Figure 15: Structural perspective of the RMS amplitude attribute distribution for the top of the target interval (deeper Target) at Site NGHP-02-06 in the southern part of Area C. Contour Interval 5ms (TWT). An opacity filter used to show only the distribution of upper band high amplitudes (red). Green arrow shows the north direction.

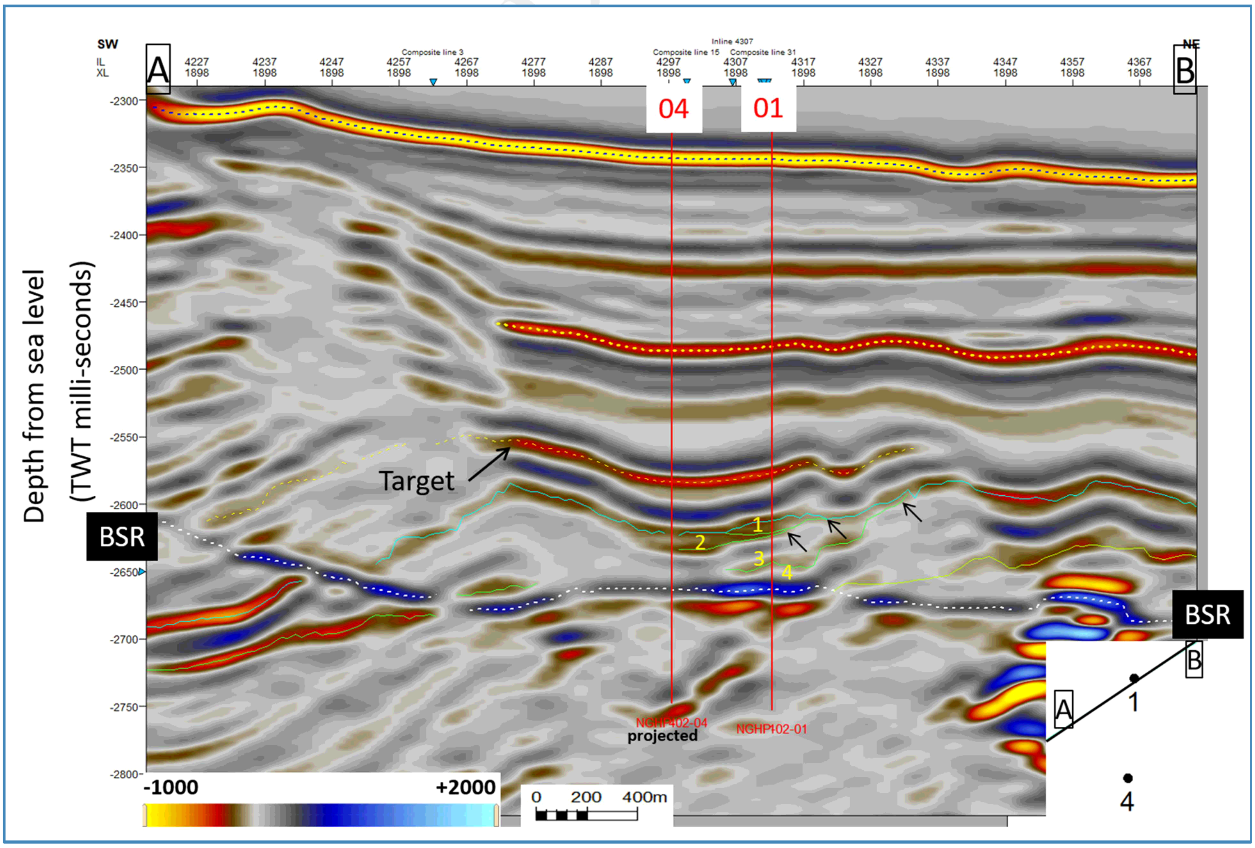

Figure 16: Seismic cross section E-F passing through two drilled sites (Sites NGHP-02-01 and NGHP-02-04) in the SW part of Area E. A BSR is interpreted and the evaluated targets (site 01) are a series of stacked (yellow 1,2,3,4) minor events near the base of the GHSZ. Red vertical lines are showing position of sites selected. Initially 01(NGHP-02-01) site was selected and drilled, Site 04 selected onboard during NGHP-02 operation and drilled as NGHP-02-04. Data phase approximates the European convention.

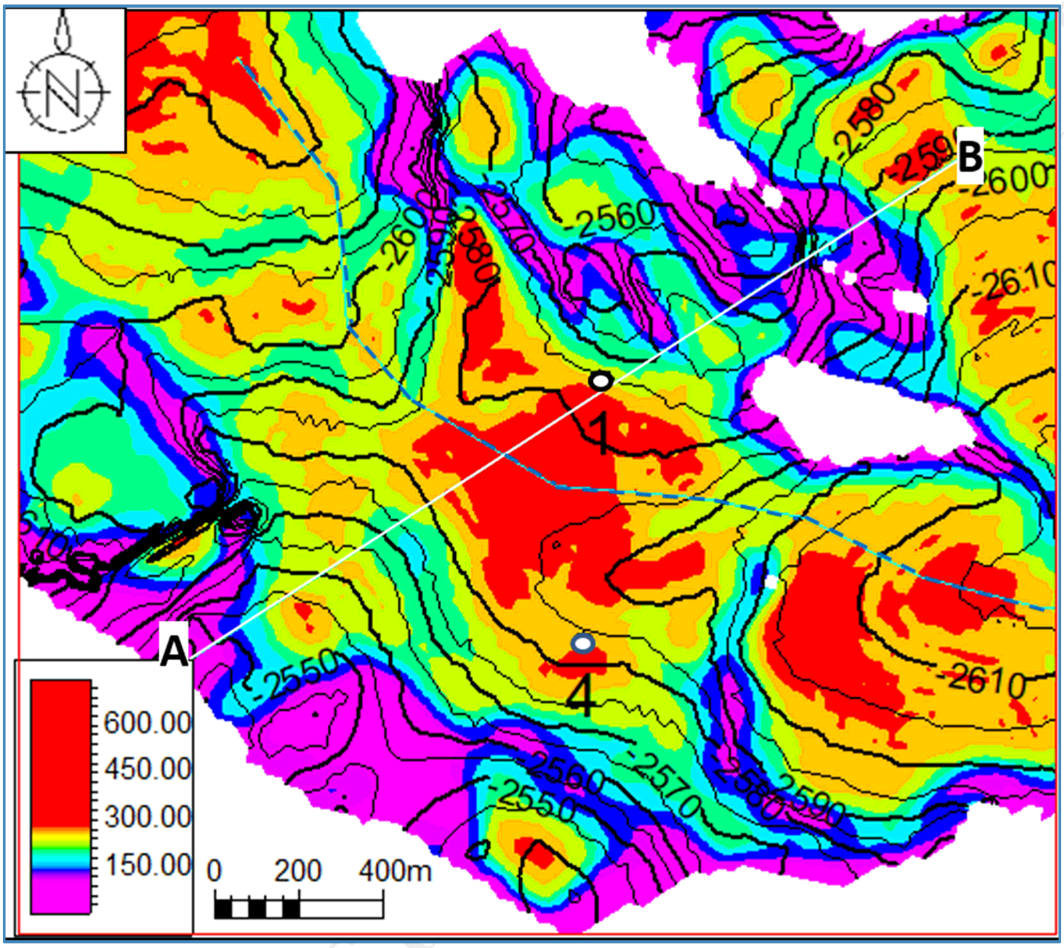

Figure 17: Structural perspective of the distribution of RMS amplitude for the target (horizon mapped) of Sites NGHP-02-01 and NGHP-02-04, suggesting presence of a feeder channel and associated coarse sediment rich fan. Topography is almost flat in the fan region. Blue dotted line indicates the main channel axis and the blue dashed line is probably a feeder channel.

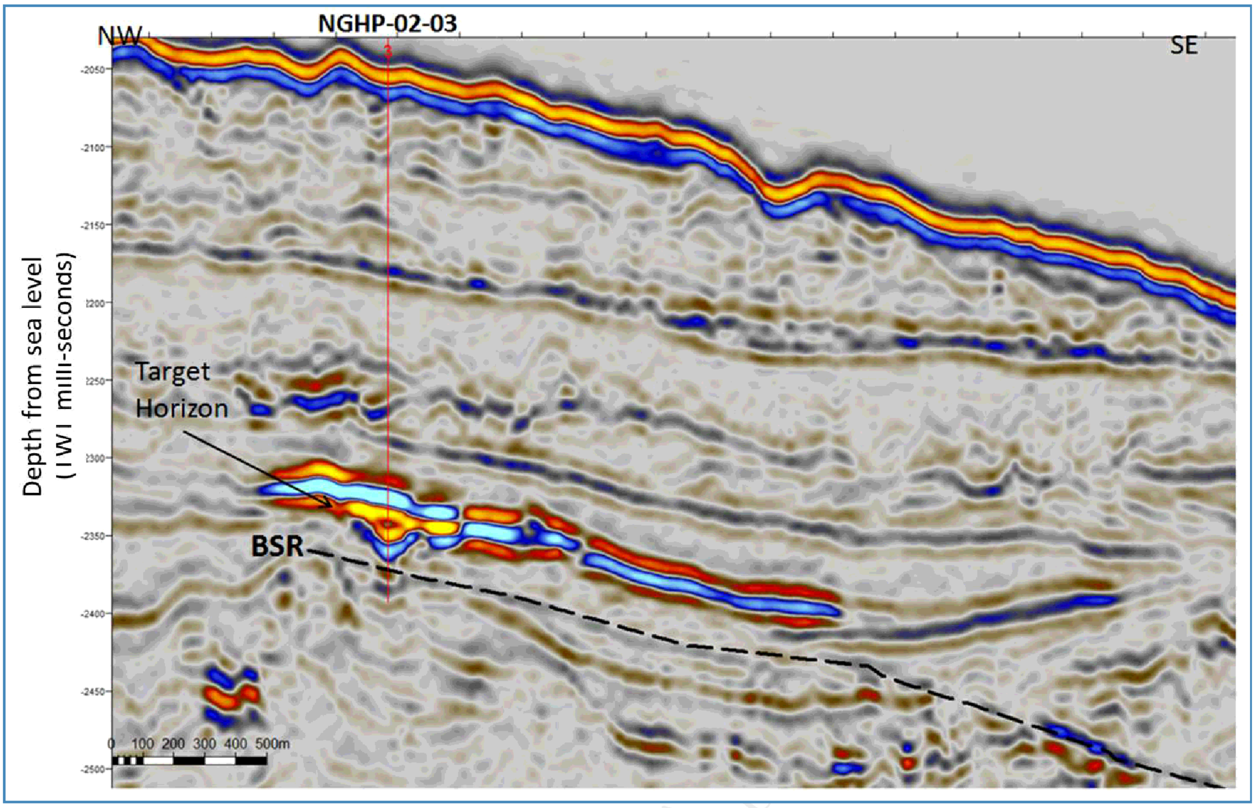

Figure 18: Seismic section passing through site NGHP-02-03 in the proximal region of Area E, showing the targeted bright seismic horizon above the inferred BSR (black dashed line) with inferred channelized geometry. Data phase approximates the European convention.

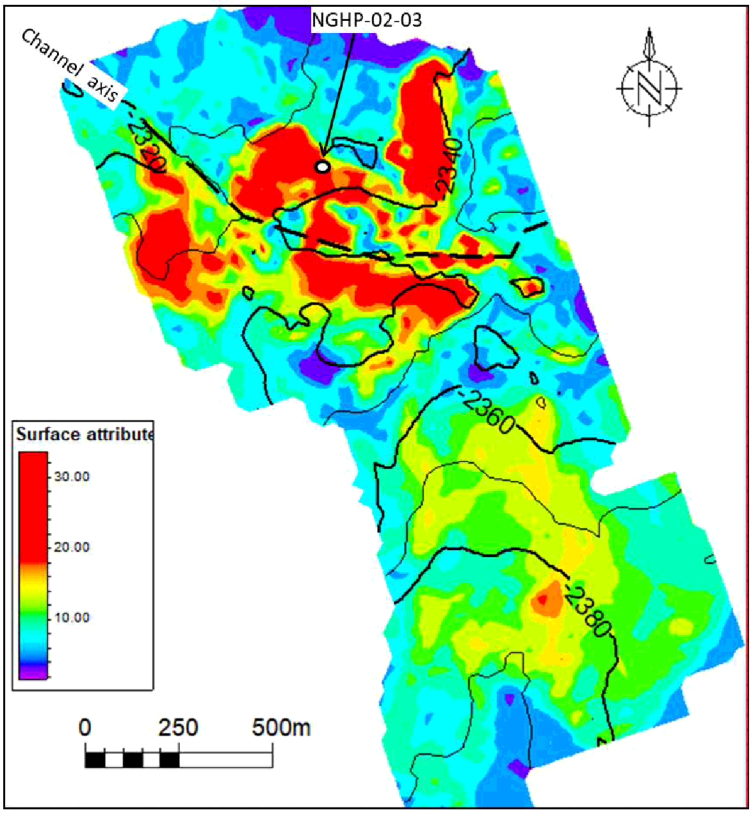

Figure 19: Structural perspective of the distribution of RMS attribute for the target horizon at Site NGHP-02-03. A feeder channel (black dash line) is associated with strong amplitude on the flanks in several lobes (discrete red color areas) that are interesting gas hydrate targets. Contour interval is 10 ms (TWT).

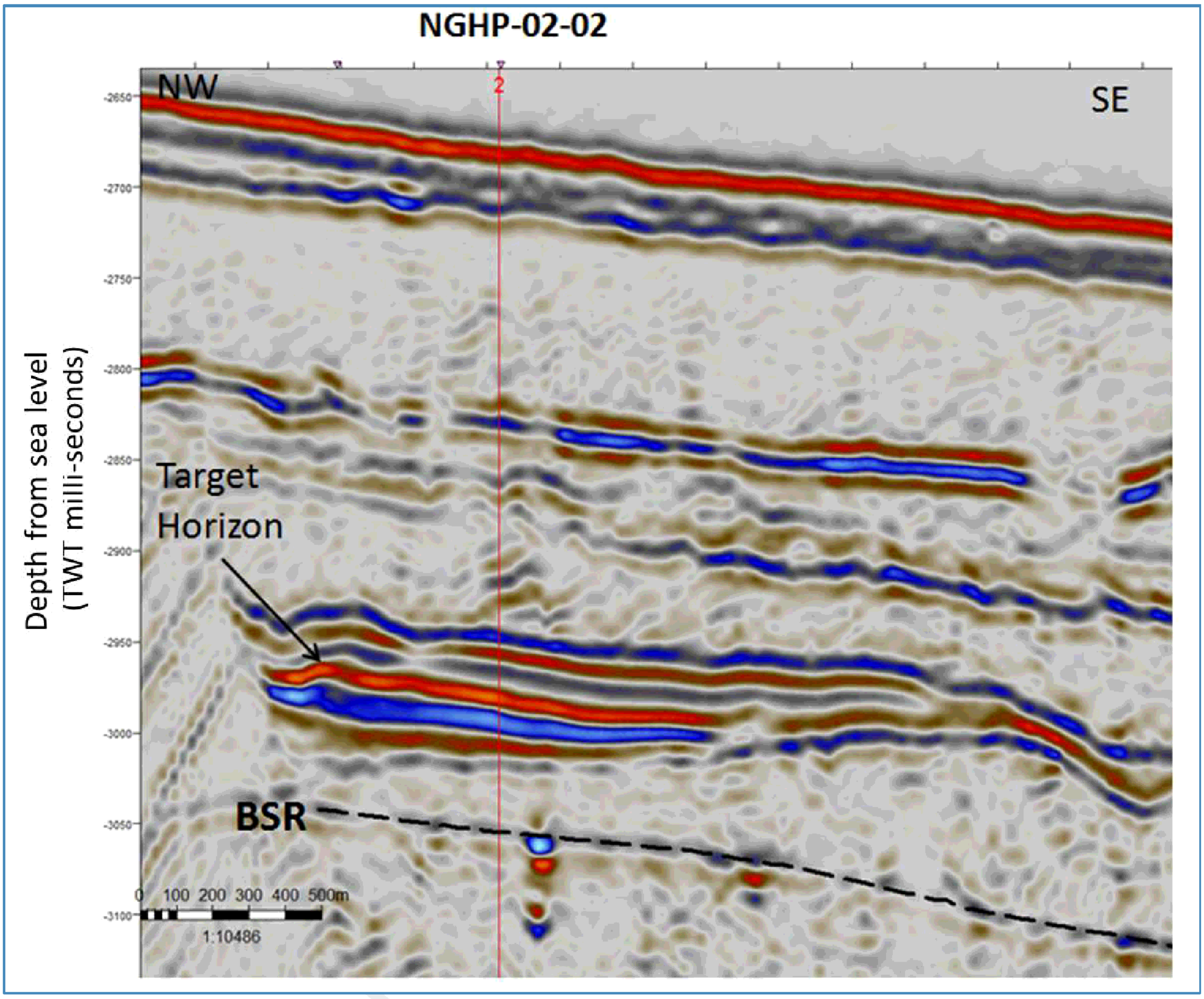

Figure 20: Seismic section passing through Site NGHP-02-02, showing targeted bright seismic (mapped) horizon (Fig. 21) above the inferred BGHS (noted as "BSR").

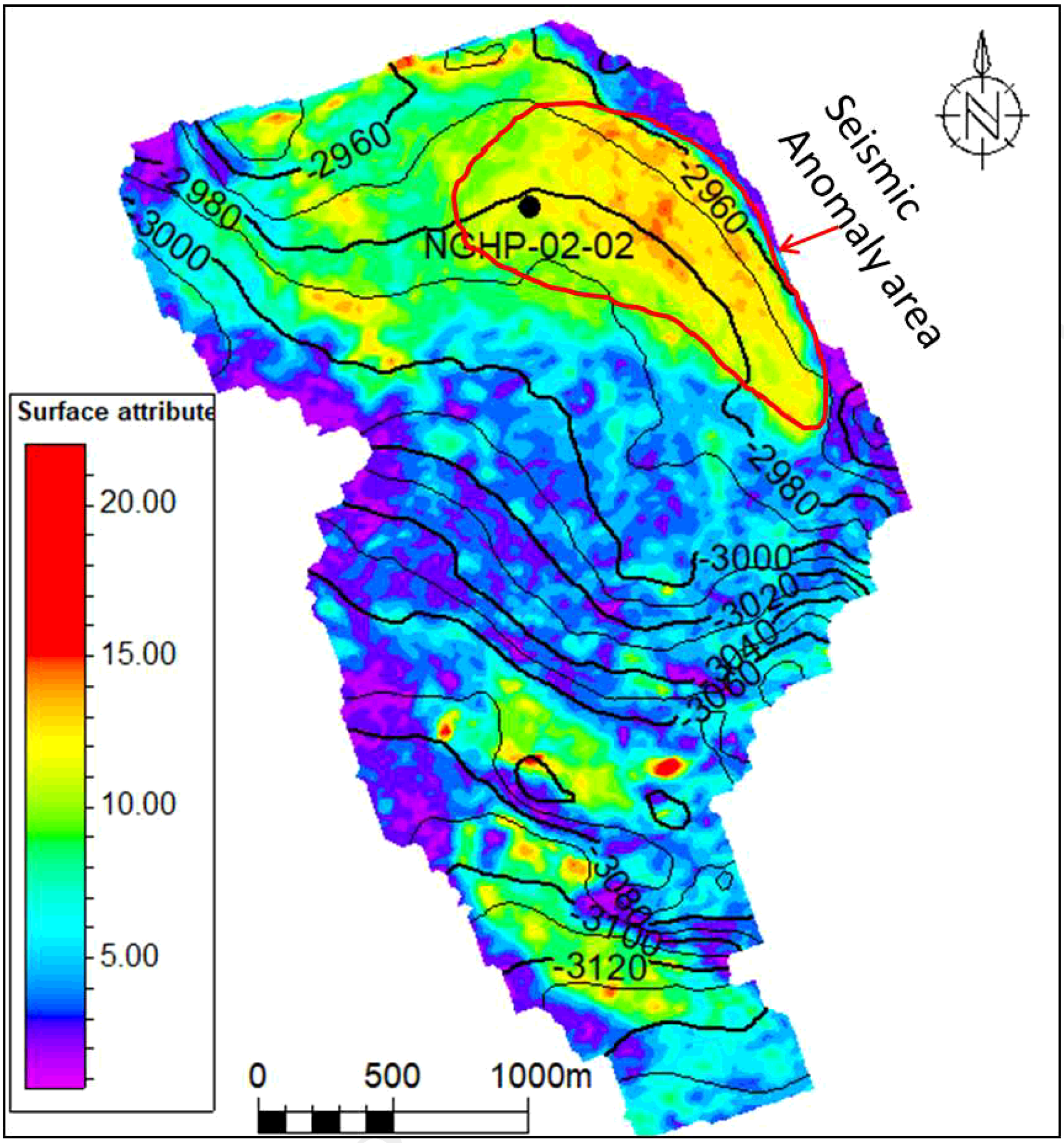

Figure 21: Structural perspective of the distribution of RMS attributes for the target horizon at Site NGHP-02-02.

Table-1: NGHP-02 Gas Hydrate Review Data					
Sl. No.	**Permit Area**	**Type of seismic polarity**	**Proposed Site**	**Drilled well site**	**Type of Geologic Feature**
1	B	American - 90^0 Phase	11A	ND	Cut-and-fill features
2			12A	ND	Cut-and-fill features
3			13A	NGHP-02-21	Cut-and-fill features
4			14A*	NGHP-02-15	Anticline folded structure
5			15A*	NGHP-02-14	Anticline folded structure
6			16A	NGHP-02-19	Channel levee feature
7			17A	NGHP-02-25	Cut-and-fill features
8			18A*	NGHP-02-18	Channel levee feature
9			23A *	NGHP-02-16	Channel levee feature
10			24A	NGHP-02-17	Channel levee feature
11			25A	NGHP-02-20	Cut-and-fill features
12			26A	NGHP-02-22	Cut-and-fill features
13			27A	ND	Channel levee feature
14			28A	ND	Onlapping syndepositional fill
15			29A	ND	Channel levee feature
16			31A*	NGHP-02-23	Channel levee feature
17			32A*	NGHP-02-24	Cut-and-fill features
18	C	American	D6-GH-1-1*	NGHP-02-09	Channel levee feature
19			D6-GH-1-2	NGHP-02-08	Channel levee feature
20			D6-GH-2-1A	NGHP-02-10	Channel feature
21			D6-GH-2-1*	NGHP-02-07	Channel feature
22			D9-GH-1-1*	NGHP-02-05	Broad anticline fold structure
23			D9-GH-2-1*	NGHP-02-06	Broad anticline fold structure
24			D9-GH-2-2	ND	Broad anticline fold structure
25	E	European	3B*	NGHP-02-01	Onlapping channel-like feature
26			3B-1	NGHP-02-04	Onlapping channel-like feature
27			D3-GH-1-1*	NGHP-02-02	Stacked onlapping fan-like feature
28			D3-GH-2-1*	NGHP-02-03	Channel/fan sequence
ND: Not drilled					
*** marked proposed sites are identified as primary sites, unmarked sites are alternate sites**					

- The pre-dill assessment of seismic data yielded identification of total 22 gas hydrate prospective sites.

- The paper details the pre-expedition studies for identification of 18 Gas hydrate prospects.

- On-board dynamic review studies for delineation of pre-expedition sites also detailed.

- The drilling results matched with pre-expedition prediction, validated approach adopted for gas hydrate prospecting.